This document is guaranteed to be current only to issue date.

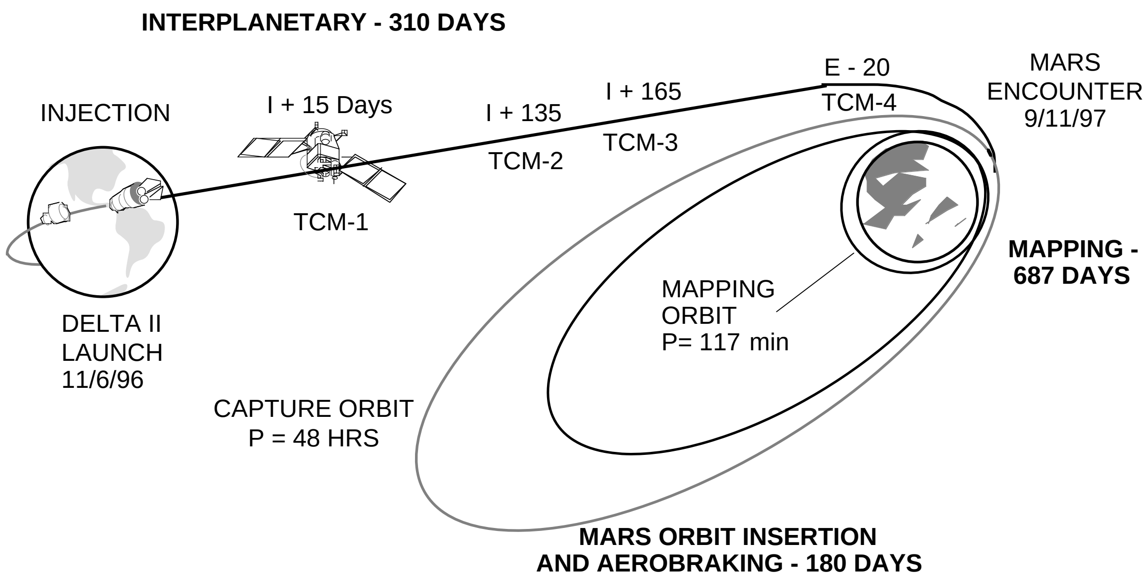
Some Mars Global Surveyor documents that relate to flight operations are under revision to accommodate the recently modified mission plan.

Documents that describe the attributes of the MGS spacecraft are generally up-to-date.

542-406, Rev B

Mars Global Surveyor

Navigation Plan - Final



August, 1996

JPL

Jet Propulsion Laboratory
California Institute of Technology

JPL D-12002

542-406, Rev B

Mars Global Surveyor

Navigation Plan - Final

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JPL D-12002

MARS GLOBAL SURVEYOR

NAVIGATION PLAN - FINAL

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The following reviewed the draft of this plan and provided suggestions for improvement: J. Beerer, S. Dallas and W. Sjogren.

The Delta-V (i. e. velocity-change) allocation tables in Appendix 9.16 were taken from the Mission Plan (provided by M. D. Johnston).

1. INTRODUCTION

1.1 PURPOSE

This document specifies the Navigation Plan for the Mars Global Surveyor Mission to Mars. When in final form, it presents a complete plan for the determination, evaluation and modification to the spacecraft's flight path throughout the mission. This plan starts after the spacecraft is injected into the Earth-Mars interplanetary trajectory by the Delta II launch vehicle. It continues through the interplanetary, orbit insertion, mapping and relay phases of the mission. From launch (11/6-25/96) until the end of the mapping phase (~1/31/2000) encompasses an operational mission duration of almost three years and three months. An additional six months are allocated to the relay phase.

The planned publication schedule for the Navigation Plan is given in Table 1.1.

TABLE 1.1 NAVIGATION PLAN PUBLICATION SCHEDULE

Navigation Plan And Date	Summary of Changes
Navigation Plan - Preliminary (542-406) September, 1994	-----
Navigation Plan - Final / Draft (542-406, Revision A) August, 1995	Input/update spacecraft-specific information. Complete propulsive maneuver analysis Complete aerobraking analysis.
Navigation Plan - Final (542-406, Revision A) September, 1995	Updates to draft as necessary.
Navigation Plan - Final / Update (542-406, Revision B) August, 1996	Updates for mission changes influencing navigation.

1.2 NAVIGATION SYSTEM AND FUNCTIONS

The flight operations navigation subsystem is a component of the mission operations system (MOS). It consists of a team of trained personnel with the appropriate interfaces for the reception, analysis and dissemination of navigation related information and the required tools to carry out the objectives presented in this document. A summarized overview of navigation functions is:

(1) Navigate the spacecraft to Mars, insert it into a specific capture orbit, develop propulsive maneuver parameters (i.e. velocity corrections) and implement the aerobraking plan to establish a specific mapping orbit, and maintain the spacecraft in the mapping orbit for the duration of the mapping phase. After mapping, establish the relay phase orbit and proceed with navigation activities according to Project guidelines,

(2) Review and provide inputs to the Spacecraft Requirements Document (S/C RD) to allow adequate understanding of spacecraft functions influencing navigation,

(3) Specify data types, calibration and accuracies necessary to establish or satisfy orbit determination (OD) accuracies,

(4) Determine accuracy requirements on various geophysical and astrodynamical models consistent with OD accuracy requirements,

(5) Conduct an orbit determination and propulsive maneuver study on all phases of the mission,

(6) As necessary, investigate strategies for improved OD performance,

(7) Determine and jointly develop or provide interfaces for the reception and dissemination of navigation related information. Information is being transferred via a distributed system of workstations. The project data base (PDB) acts as the central reservoir for the accumulation and dissemination of all operational information. In particular, navigation products are deposited into the PDB and products required by navigation from other project elements are to be retrieved from the PDB.

At present, the DSN required trajectory information (P-files) is being delivered to the DSN node called OSCAR. Orbit data files (ODF) are being delivered to Navigation by that same interface.

(8) Develop a coherent time-line with other project elements for the timely dissemination of navigation products.

1.3 RELATIONSHIP TO OTHER DOCUMENTS

This Navigation Plan is consistent with and responsive to the requirements and objectives of the following documents:

- Mission Requirements (MRD) : 542-400
- Investigation Description and Science Requirements (ID/SRD): 542-30
- Mission Plan (MP) : 542-405

Additional reference documents include:

- Spacecraft Requirements (S/C RD)
- Trajectory Characteristics (TCD)
- Planetary Constants and Models
- Mission Operation Specifications
- Mission Requirements Request (MRR)
- Planetary Protection Policy
- Delta II Target Specification

as well as those provided in Section 8.

2. REQUIREMENTS

2.1 MISSION DESIGN REQUIREMENTS LEVIED ON NAVIGATION DESIGN

This section provides a summary of mission design requirements levied on navigation design. It provides the information that navigation design needs in order to determine 1) how well navigation can achieve mission objectives and 2) what capabilities or resources are necessary to achieve mission objectives. Mission requirements (MR) in chronological order, are summarized in Tables 2.1 through 2.4. Review the Mission Requirements Document (MRD -- Ref. 2.1) and the Investigation Description and Science Requirements Document (ID/SRD- Ref. 2.2) for a complete specification of the requirements.

TABLE 2.1 MISSION REQUIREMENTS DURING THE INTERPLANETARY PHASE

- Mission Delta-V Allocation (MRD 3.2.1)

  Delta-V = 52.9 m/s and 975.6 m/s and for TCMs (this includes the injection aim point bias) and MOI respectively. This covers the interplanetary phase and the MOI propulsive maneuver; this specifies the Delta-V capability (excluding the attitude control function) to insure that the spacecraft can be delivered to the capture orbit. The Delta-V allocation for the TCMs is the 95th percentile confidence.

- Adhere to NASA Planetary Protection Policy (MRD 3.2.3)

  This policy is summarized in Section 6.

- Payload Sun Avoidance (MRD 3.2.11)

  Do not design propulsive maneuvers which places the spacecraft axis normal to the nadir panel within 30 degrees of the solar direction.

TABLE 2.2 MISSION REQUIREMENTS DURING THE ORBIT INSERTION PHASE

- Mission Delta-V Allocation (MRD 3.2.1)
  The Delta-V (translational) allocated for the orbit insertion and aerobraking phase is 149.0 m/s. See Appendix 9.16 for the current, nominal Delta-V sub-allocation.

- Adhere to Planetary Protection Policy (see Table 2.1)

- Spacecraft Overheating Avoidance During Mars Capture (MRD 3.2.2)
  The spacecraft's altitude during the first periapsis after capture shall be greater than 150 km. This avoids atmospheric heating damage to the spacecraft.

- Payload Sun Avoidance (see Table 2.1)

- Propulsive Aerobraking Maneuver Frequency (MRD 3.2.8)
  Develop capability to support aerobraking maneuvers every day.

- Aerobraking Phase Orbital Accuracy (MRD 3.2.10)
  Time of periapsis passage shall be known to 225 s .
  Radial distance at periapsis shall be known to 1.5 km .

  Note that the timing requirement stems from the spacecraft’s angle of attack constraint during the drag or periapsis pass. Failure to maintain the timing accuracy results in increased propellant usage to maintain the spacecraft’s attitude.

TABLE 2.3 MISSION REQUIREMENTS DURING THE MAPPING PHASE

- Delta-V Allocation: Delta-V = 3.9 m/s (MRD 3.2.1)
  This covers all orbit maintenance maneuvers.

- A Delta-V of 12. m/s has been allocated for the execution of a quarantine orbit maneuver. (MRD 3.2.1)

- Payload Sun Avoidance (see Table 2.1)

- Mapping Orbit Specification (MRD 3.2.4)
  The spacecraft shall be established in the following mapping orbit (mean values) with respect to the Mars equator and IAU vector of epoch (T: days past 1/1/98).

Element	Value
a (km)	3775.1
e	0.0072
I(deg)	92.87
Ω(deg)	-39.1664 + 0.524*T
ω(deg)	-90.0

  These elements were derived for a frozen orbit with respect to the J2 and J3 terms of the Balmino gravity field. The Balmino gravity field is quite old. More accurate gravity fields currently exist. Furthermore, only using the J2 and J3 terms is not accurate. Therefore new orbital elements were derived and are shown below.

- New Mapping Orbit Specification (E-mail from Daren Casey, 7/29/96)
  The spacecraft shall be established in the following mapping orbit (mean values) with respect to the Mars equator and IAU vector of epoch (T: days past 1/15/98 01:00:00).

Element	**Mean**	**Osculating**
a (km)	3774.997666310	3765.939690361
e	0.009526333	0.006338350
I (deg)	93.010617978	93.014163471
Ω (deg)	328.19262449793 + 0.524043 * T	328.19262449793 + 0.524043 * T
ω (deg)	-90.0	-90.0

  These new elements were derived for a frozen orbit with respect to the MARS50C 50x50 gravity field.

TABLE 2.3 MISSION REQUIREMENTS DURING THE MAPPING PHASE (cont)

- Mapping Orbit Bounds (MRD 3.2.5)
  The mapping orbit shall be maintained within these bounds about the above mean:

Element	Bound
a (km)	+0.7 to -1.2
e	≤ 0.014 (upper bound)
Ω (deg)	± 3.
ω (deg)	± 10.

- Spacecraft Position -- 14 Day Prediction Accuracy (MRD 3.2.6)
  The predicted position of the spacecraft shall be within the following accuracy (3 sigma):

Position Component (km)	Perihelion 1 (1/7/98)	Perihelion 2 (11/25/99)
Downtrack (DT)	20*	150*
Crosstrack (CT)	9	9
Radial (R)	8	8

  *These uncertainties were driven by the atmospheric density; a 95% confidence level was used.
  Note that due to mission timeline changes, perihelion1 is no longer within the mapping phase.

- Orbit Reconstruction Accuracy During the Mapping Phase (MRD 3.2.7)
  The reconstructed position of the spacecraft shall be known within the following accuracy (3 sigma) and excludes solar conjunction:

Position Component	Accuracy (km)
Downtrack (DT)	9
Crosstrack (CT)	5
Radial (R)	2

  This accuracy is required by the science teams for the processing and analysis of science data.

- Orbit Trim Maneuver (OTM) Frequency During the Mapping Phase (MRD 3.2.9)
  OTMs shall not be performed more frequently than every 14 days.

TABLE 2.4 MISSION REQUIREMENTS DURING THE RELAY PHASE

- Payload Sun Avoidance (see Table 2.1)

- Relay Phase Orbit (MRD 3.2.12, also Table 6.1)

  The spacecraft shall be established in the following relay orbit (mean values; 400. km index altitude) with respect to the Mars equator and IAU vector of epoch (T: days past 1/1/98).

Element	Value
a (km)	3797.2
e	0.0072
I(deg)	92.93
Ω(deg)	-39.1664 + 0.524*T
ω(deg)	-90.0

- Updated Relay Phase Orbit (M. D. Johnston, 8/8/96)

  The relay orbit has recently been changed. It is currently with respect to a 414. km index altitude. Its mean orbital elements are listed below, with respect to the Mars equator and IAU vector of epoch 2/1/2000.

Element	Value
a (km)	3811.2
e	0.0072
I(deg)	93.01
Ω(deg)	-0.4
ω(deg)	-90.0

- Delta-V Allocation (MRD 3.2.1)

  A Delta-V of 4.8 m/s (95th percentile) has been allocated for OTMs. See Appendix 9.16 for the current, nominal Delta-V sub-allocation.

3. NAVIGATION OVERVIEW

The event time-line given in the following three tables summarize major navigation events.

TABLE 3.1 INTERPLANETARY PHASE EVENTS

Date	Event
11/06/96 to 11/25/96	Twenty day launch period. Nominal launch (L) and injection (I) into the earth-to-Mars transfer trajectory occur on 11/06/96.
11/21/96 (I + 15 days)	First trajectory correction maneuver (TCM-1); it corresponds to (I + 15 days) for all injection dates. It will correct the flight path for execution errors associated with the injection and reduce the injection bias due to planetary protection requirements.
03/21/97 (I + 135 days)	TCM-2; it is coupled with the previous maneuver in order to "optimize" or minimize spacecraft fuel consumption and occurs at TCM-1 + 120 days for the first launch date. The targeted B-plane aim-point will move closer to the final aim-point with allowance for planetary protection requirements.
04/20/97 (I+165 days)	TCM -3; it occurs at TCM-2 + 30 days and adjusts the B-plane targeting based upon results of the previous maneuvers.
08/22/97 (I + 289 days or E-20 days)	TCM 4; final adjustment of the target aimpoint at Mars as necessary.
09/11/97 to 09/22/97	Mars encounter (E) dates corresponding to the launch date. The nominal encounter (unbraked) for the first launch date is 9/11/97, 01 hr 28 min (ET, SCET); this corresponds to 9/10/97, 18 hr 40 min (PDT, ERT)

TABLE 3.2 ORBIT INSERTION AND AEROBRAKING PHASE EVENTS

Date	Event
09/11/97	Mars orbit insertion (MOI) maneuver; this date corresponds to the first launch date. The maneuver is being planned as a "pitch-over" maneuver and shall start prior to periapsis with engines thrusting for approximately 24 minutes. The space-craft's velocity shall decrease by approximately 0.976 km/s to allow capture into an orbit with a 48 hour period. The orbit insertion phase starts with this maneuver and ends when the spacecraft is declared ready to start mapping phase operations; this interval is approximately 180 days.
09/20/97 (MOI + 9 days)	First post-encounter propulsive maneuver (AB-1); it shall lower the periapsis distance and adjust the orbital inclination .
09/20/97 to 10/11/97	The start of the “walkin” phase of aerobraking (AB) begins at the end of AB-1. Three additional propulsive maneuvers (AB-2, AB-3 and AB-4) shall successively lower the periapsis distance.
10/11/97 to 01/02/98	Series of n aerobraking maneuvers (ABM-n) during the “main” phase of aerobraking (nominally n = 15). These shall be designed to maintain the spacecraft and orbit within the aerobraking corridor.
01/02/98	Start of “walkout” phase of aerobraking (duration of 22 days). The altitude of periapsis shall be successively increased by a series of approximately 20 maneuvers. This phase shall terminate with a final AB maneuver called ABX. It shall raise the periapsis altitude.
01/07/98	Mars perihelion.
01/23/98 to 02/17/98	This interval (approx 25 days) starts with ABX and ends with the transfer-to -mapping orbit (TMO) propulsive maneuver. During this time, the argument of periapsis will drift naturally to the South Pole. The GC analysis shall be based upon tracking data acquired during this interval.

TABLE 3.2 ORBIT INSERTION AND AEROBRAKING PHASE EVENTS (CONT.)

Date	Event
02/17/98	The TMO maneuver shall establish or transfer the spacecraft to the mapping orbit which shall also be sun-synchronous at the 2:00 p.m. descending node.
03/01/98	The first orbit trim maneuver (OTM-1) shall be required to correct any remaining errors in the mapping orbit and establish a “ frozen orbit “ .

TABLE 3.3 MAPPING PHASE EVENTS

Date	Event
03/11/98	Start of the mapping phase of the mission ; its duration is 687 earth days or one Mars year. The spacecraft's orbit is a 7 day repeat cycle with a nominal 58.6 km eastward walk.
03/20/98	Orbit trim maneuver (OTM-2) to adjust frozen orbit elements as necessary (approximate date).
05/13/98	Solar conjunction. For navigation, a solar conjunction phase is defined whenever the sun-earth-Mars (SEM) angle is less than or equal to 3 deg; this occurs from May 1 to May 30.
10/29/98	This is the edge-on MGS orbital configuration as seen from earth (Ipos = 90 degrees or earth beta angle equals zero degrees). Within 14 days of this date, differenced doppler data are required for orbit determination.
01/04/99	At this time, the MGS orbit is 4.9 deg away from edge-on and then it moves back toward edge-on.
02/19/99	Second edge-on orbital configuration as seen from earth. Differenced doppler is required with 14 days of this configuration for orbit determination. Note that the spacecraft's orbit is within 5 deg of edge-on for approximately 5.5 months.
05/02/99	Earth-Mars distance is minimum (0.578 AU; OWLT = 4 min 49 sec).
09/22/99	Minimum Ipos (= 12.3 deg)
11/25/99	Mars perihelion
01/31/00	End mapping phase; initiate relay phase.

3.1 INJECTION CONDITIONS AND UNCERTAINTIES

The current injection conditions and uncertainties are summarized in Appendix 9.1 During flight operations, these shall be used as the initial conditions to start the orbit determination and analysis process. The uncertainties will allow navigation to assess the launch-vehicle-system performance from both an injection accuracy and maneuver target specification.

At the target interface point (TIP = 11/06/96, 18:06 ET, SCET, first launch), the spacecraft's position uncertainties (one sigma) are 20. km, 0.3 km, and 1.6 km in the DT, CT and R components respectively.

3.2 INTERPLANETARY PHASE CHARACTERISTICS

The interplanetary trajectory characteristics are summarized in the following figure. It shows the ecliptic view of the earth-to-Mars trajectory from launch to encounter. Encounter parameters are summarized in the following table.

TABLE 3.4 MGS ENCOUNTER (9/11/97) CHARACTERISTICS

Quantity	Geocentric	Heliocentric
Distance (x 10^6 km)	253.8	219.6
One-way light time	14 min 4.7 s	---
RA / Cel. Longitude (deg)	225.1	264.0
DEC / Cel. Latitude (deg)	-18.0	-1.05
Velocity (km/s)	32.8	20.6

Figure 3.1 MGS Earth to Mars interplanetary trajectory

3.2.1 SPACECRAFT CONFIGURATION

The spacecraft's configuration during the interplanetary, aerobraking and mapping phases of the mission is given in Appendix 9.2

There are several basic areas that navigation requires information from Lockheed-Martin Astronautics (LMA) for development and flight operations. These involve solar radiation pressure (SRP), non-gravitational (NG) force (primarily angular momentum desaturations, AMD) models, the spacecraft's ballistic coefficient (= m / ($C_d * A$)) and the spacecraft's attitude.

The interplanetary phase is divided into an inner (telecommunications via the low-gain antenna) and outer (telecommunications via the high-gain antenna) cruise segment with the transition occurring in January, 1997. In the inner cruise phase, the spacecraft's +X axis is off pointed from the sun by varying amounts and slowly rotating (for star scanning) with a period of 100 minutes. Thus a sinusoidal signature will be embedded in the doppler and range data. During outer cruise, the +X axis is pointed directly at the earth while the spacecraft is still rotating as above. However, no rotational signature will be embedded in the tracking data. This nominal configuration is called array-normal-spin (ANS) and is exercised until the mapping phase begins. Some basic physical features of the spacecraft are given in the following table.

TABLE 3.5 SPACECRAFT PHYSICAL INFORMATION

Injected Mass (kg)	1060.
Solar Array Dimensions (L x W , m)	3.531 x 1.854
Flap Size (L x W , m)	0.813 x 1.734
Equipment Module (L x W x D, m)	1.221 x 1.221 x 0.762
Propulsion Module (L x W x D, m)	1.063 x 1.063 x 0.310
HGA (Diameter; Depth, m)	1.5 ; 0.26
HGA Boom Length (m)	2.0
Ballistic Coefficient for Aerobraking (kg/m^2)	22.42
Mass (kg)	745.
Cd (continuum region)	1.95
Area (m^2)	17.04
Ballistic Coefficient for Mapping (kg/m^2)	22.0 (approximate)
Mass (kg)	703.
Cd (free molecular flow)	2.2
Area (m^2)	14.5

Note that the HGA will not be fully deployed until near the end of the orbit insertion phase.

The spacecraft's attitude is controlled by three reaction wheel assemblies (RWA). When the angular momentum threshold is reached, desaturation shall occur resulting in a net translational velocity imparted to the spacecraft. Telemetry for every AMD event shall be recorded on the spacecraft and shall be used to reconstruct the perturbation (effective velocity change) and modeled in the OD process.

3.3 MARS APPROACH AND CAPTURE ORBIT

The geocentric view of the MGS encounter (9/11/97) is shown in Figure 3.2 . The next two tables provide preliminary MOI maneuver and capture orbit characteristics.

Fig. 3.2 Geocentric view of MGS encounter (9/11/97).

TABLE 3.6 MOI MANEUVER CHARACTERISTICS (9/11/97)
(PITCH-OVER CAPTURE BURN)

Quantity	Nominal Value
Delta-V (m/s)	975.6
Burn duration (m:s)	24 : 36
Initial Burn Attitude	
Right Ascension (deg)	-5.76
Declination (deg)	7.20
Capture Orbit Rp (km)	3700.

TABLE 3.7 CAPTURE ORBIT CHARACTERISTICS

Quantity At Apoapsis (9/12/97, 01:14 ET)	Nominal Value
Period (hours)	48.0
Semi-major axis (km)	31670.
Eccentricity	0.883
Long. of Ascending Node (deg)	-41.40
Arg. of Periapsis (deg)	147.6
Inclination (deg)	92.86
True Anomaly (deg)	180.0
Periapsis radius / velocity (km; km/s)	3700. / 4.67
Apoapsis radius / velocity (km; km/s)	59638. / 0.29

Mars centered, Mars mean equator and IAU vector of epoch.

3.4 ORBIT INSERTION PHASE AND AEROBRAKING

This phase starts at MOI and lasts until the mapping phase begins ; its duration is 180 - 181 days for the first launch.

3.4.1 SPACECRAFT CONFIGURATION

Throughout orbit insertion, the spacecraft's nominal configuration is ANS until preparation for entry into the "drag-pass" . During periapsis passage, the +X axis shall be nadir pointed and the solar arrays swept back by 30 deg (see Appendix 9.2).

3.4.2 AEROBRAKING DESIGN

A preliminary AB design has been developed in Ref 3.2. From MOI (9/11/97, first launch) to the execution of the final AB maneuver (called ABX on 1/23/98), encompasses 135-136 days and 482 orbits. Figures 3.3 to 3.7 have been taken from this memo and are summarized as (figure number and comment) :

3.3 Orbit period variation: Starts at 48 hours and ends at 1.89 hours.
3.4 Orbit period change per orbit: Maximum near 4800 s (80 min) and approximately 70 s near the end of AB mainphase.
3.5 Altitude at periapsis: After AB-1, the altitude is 138. km and reaches a minimum of 102. km. (Note: the current design has changed the altitude after AB-1 to be 150 km.)
3.6 Atmospheric density at periapsis: After the first walkin maneuver (AB-1), the density is 2 kg/km^3 and reaches a maximum of approximately 70 kg/km^3
3.7 Propulsive Maneuvers: Their frequency and magnitude are
Walkin (4 mnvrs), ΔV (AB-1, 2, 3, 4 ; m/s) = 6.53, 0.8, 0.2, 0.05
Main phase (15 mnvrs), ΔV (m/s) between 0.05 and 0.4
Walkout (20 mnvrs), ΔV (m/s) between 0.9 and 1.3

Figs. 3.3, 3.4, 3.5, 3.6, 3.7

Several aerobraking designs have been created. This aerobraking design (Ref 3.2) was updated on 9/14/95 to be consistent with an updated first launch date of 11/5/96. The current first launch date has changed again to 11/6/96. Our results refer to the baseline established in Ref. 3.1.

3.4.3 GRAVITY CALIBRATION (GC)

The purpose of the gravity calibration phase is to develop a refined Mars gravity field model to be utilized throughout the mapping phase. This will a) provide a significant improvement in reconstructed and predicted spacecraft position and b) be used to prepare the "frozen-orbit" target orbital elements. The tracking data acquisition for this analysis has been moved from after TMO to the interval between ABX and TMO. This was done in order to minimize time in the orbit insertion phase (approximately 31 days have been saved by this decision).

However because the orbit is less desirable for gravity field analysis than the mapping orbit, Navigation has requested that the GC phase extend throughout this 25 day interval. A comparison between these two types of orbits is given in the following table. The first application of the new gravity field will be for the specification of the frozen-orbit elements for the OTM-1 maneuver.

TABLE 3.8 MAPPING-TRANSITION AND MAPPING ORBITS

PARAMETER	MAPPING TRANSITION ORBIT	MAPPING ORBIT
Epoch (ET, SCET)	1/22/98, 21:03:09	2/17/98, 00:00:00
Period (min)	119.	117.
Repeat Cycle	None	7 sols
Ground Track Separation	Varies (non-uniform)	2 deg (uniform)
Periapsis Altitude (km)	388.3	375.1
Apoapsis Altitude (km)	443.6	428.5
Periapsis Occulted	Yes	No
Occultation (m:s)	34:42	37:35
Ipos (deg)	132.9	124.0
SEP Angle (deg)	25.4	19.7

.

3.5 MAPPING PHASE

The mapping phase begins on 3/11/98 and extends for one Mars year (687 earth days) until 1/31/2000. Since the spacecraft shall be nadir pointed and acquiring science data continuously, it shall rotate once per orbit. Tracking data shall be acquired daily over a ten-hour pass and more frequently for edge-on orbital events.

3.5.1 SOLAR CONJUNCTION (5/13/98)

Mars solar or superior conjunction occurs on 5/13/98 when the spacecraft passes behind the sun. Seen from earth, this corresponds to an angular separation of 0.06 degrees; the spacecraft's geocentric distance is 372.1 x 10^6 km (2.48 AU) giving a one-way-light-time of 20 min 41 sec.

When the spacecraft is within a sun-earth-spacecraft angle of three degrees (from 5/1/98 to 5/30/98), navigation shall be on a best efforts basis. This is because the doppler data shall be degraded and completely unusable as the raypath passes closest to the sun.

The sun-earth-probe or spacecraft (SEP) angle variation during the solar conjunction is shown in Fig. 3.8.

Fig 3.8 Mars solar conjunction (5/13/98) , SEP angular variation.

3.5.2 Edge-On Orbital Configuration

There are two times during the mapping phase when the spacecraft's orbit will be edge-on as viewed from earth. On these dates (10/28/98 and 2/19/99), the inclination of the orbit plane to the plane-of-the-sky will be 90 degrees or the earth beta angle will be zero degrees. This configuration causes reduced information content in the two-way doppler data resulting in poorer orbit determination or position accuracy.

Another unique aspect of the mapping phase is that the spacecraft's orbit will be within 5 degrees of edge-on for an interval of approximately 5.5 months. This time-span is from 9/15/98 to 3/10/99 as shown in Fig. 3.9.

Fig 3.9 Orbit plane variation (Ipos) throughout mapping.

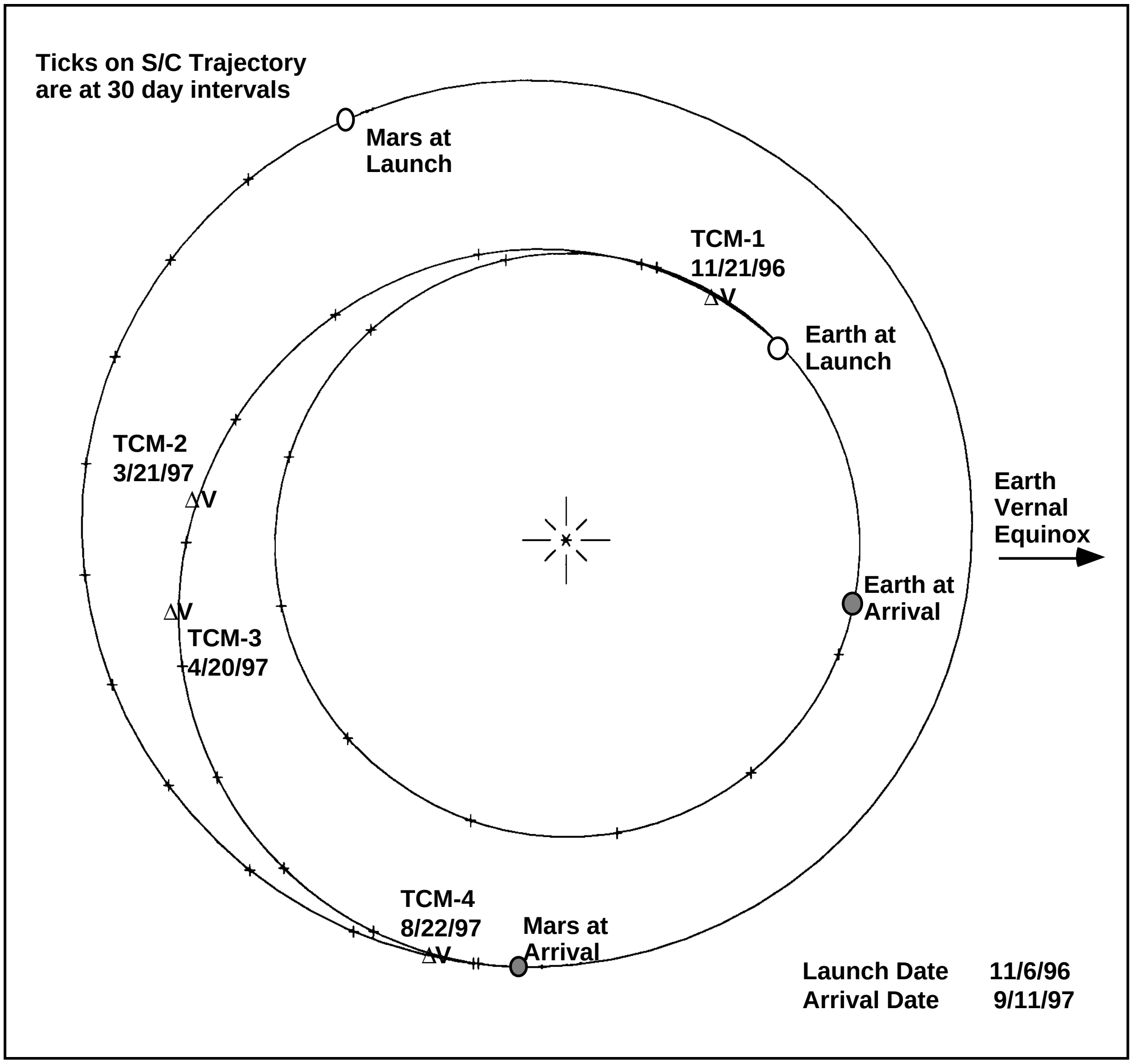


Fig. 3.1 MGS Earth To Mars Interplanetary Trajectory

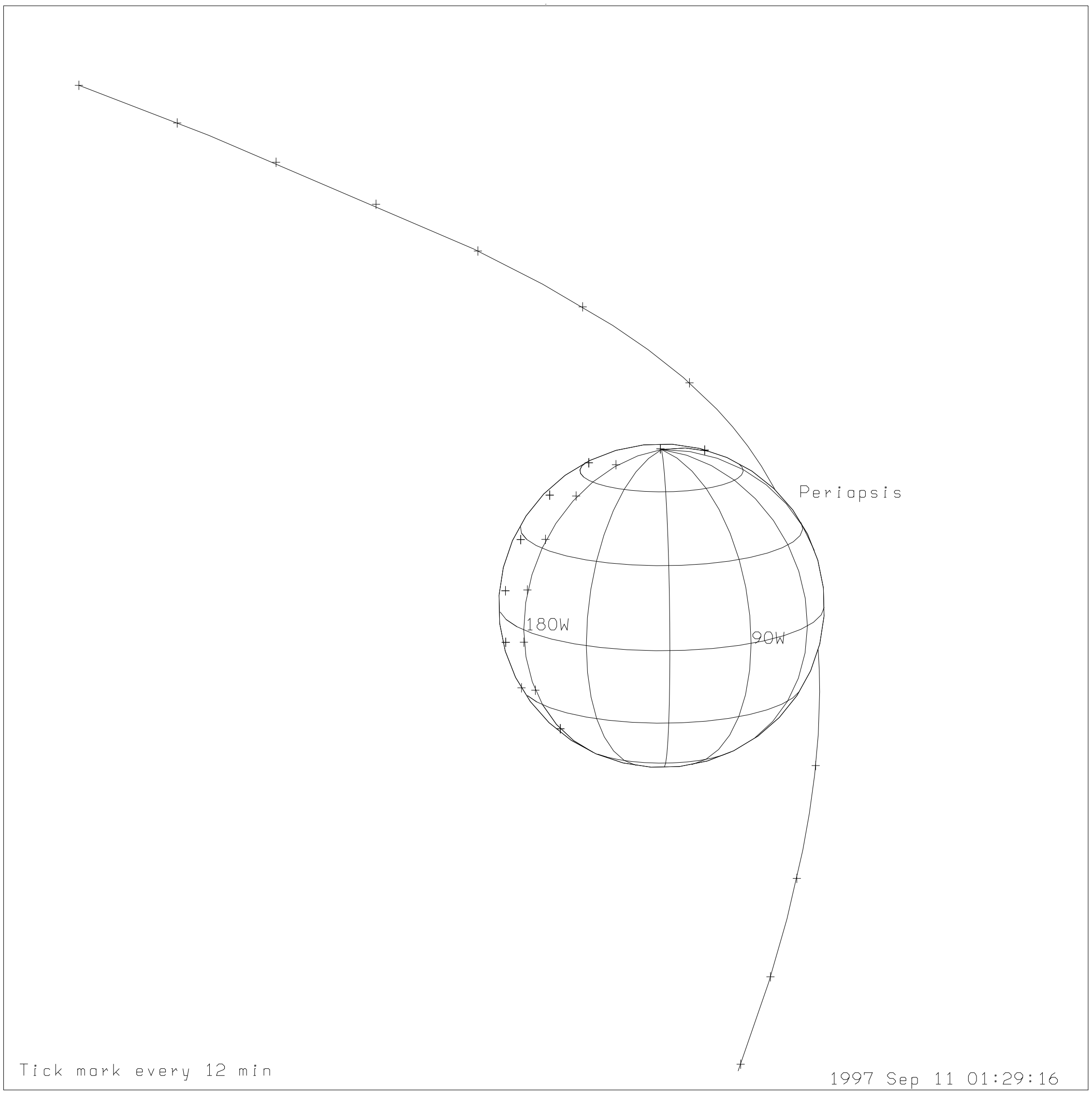


Figure 3.2 Geocentric View of MGS Encounter (9/11/97)

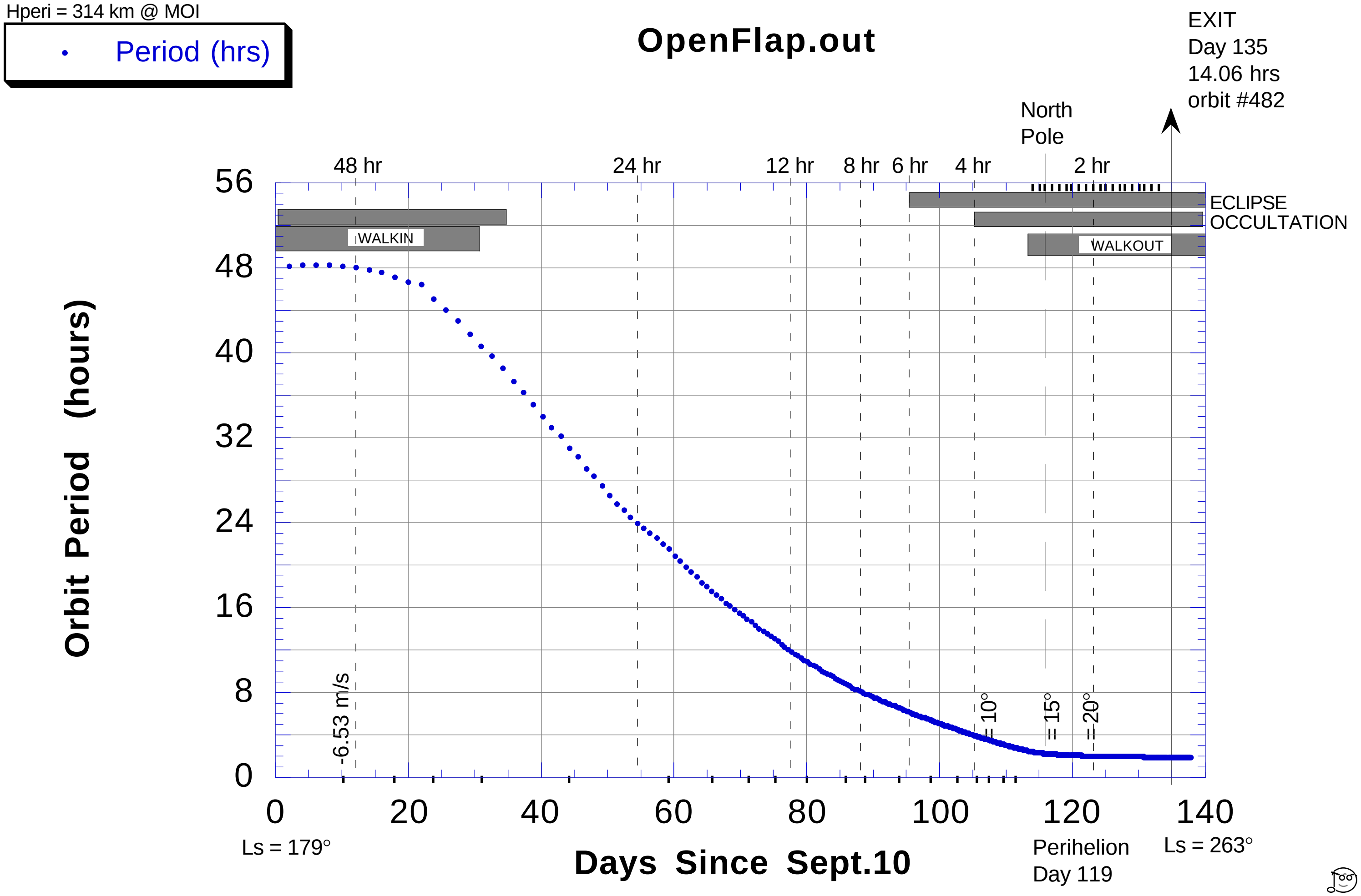


Figure 3.3 Orbit Period Variation

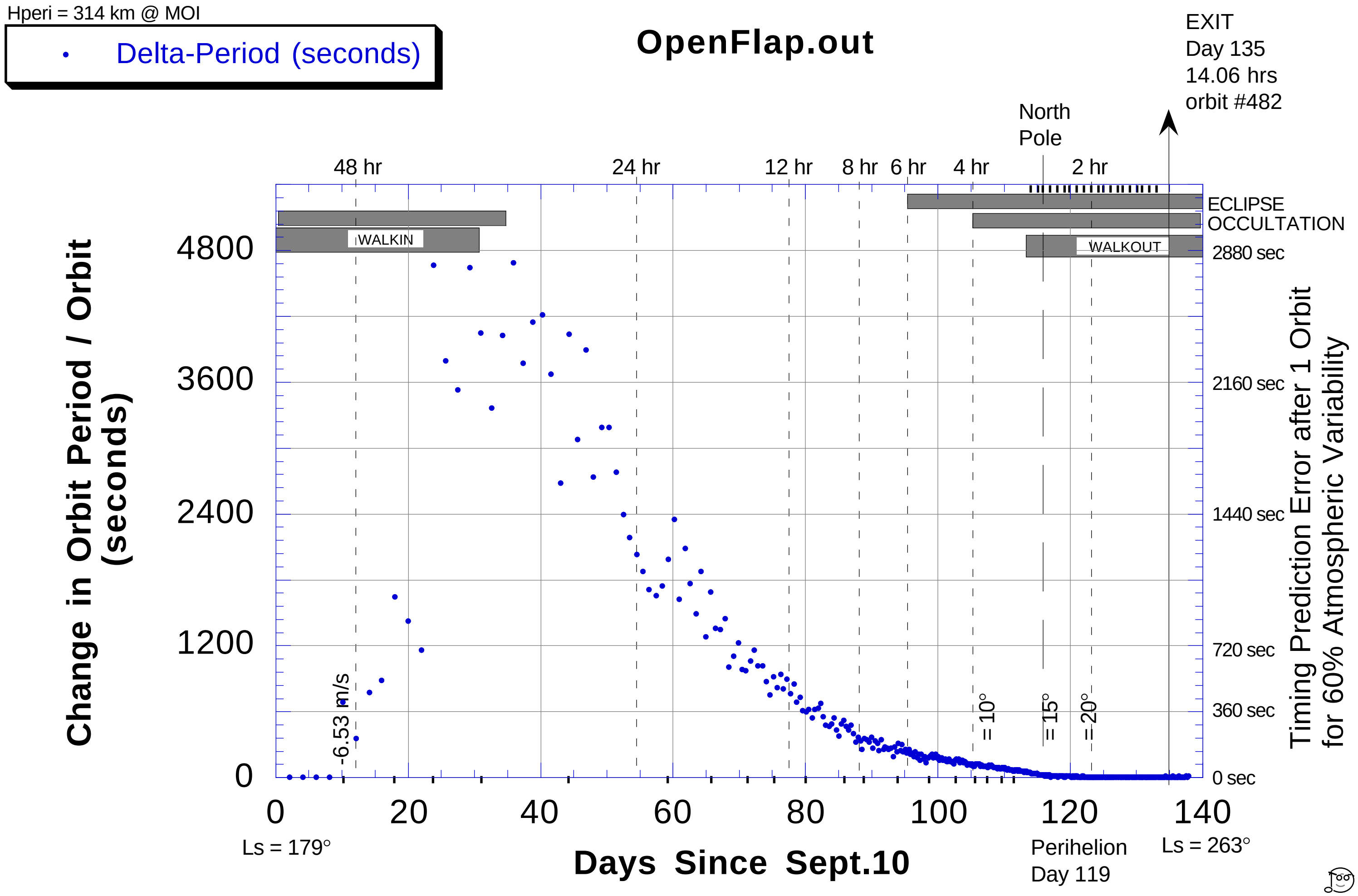


Figure 3.4 Orbit Period Change Per Orbit

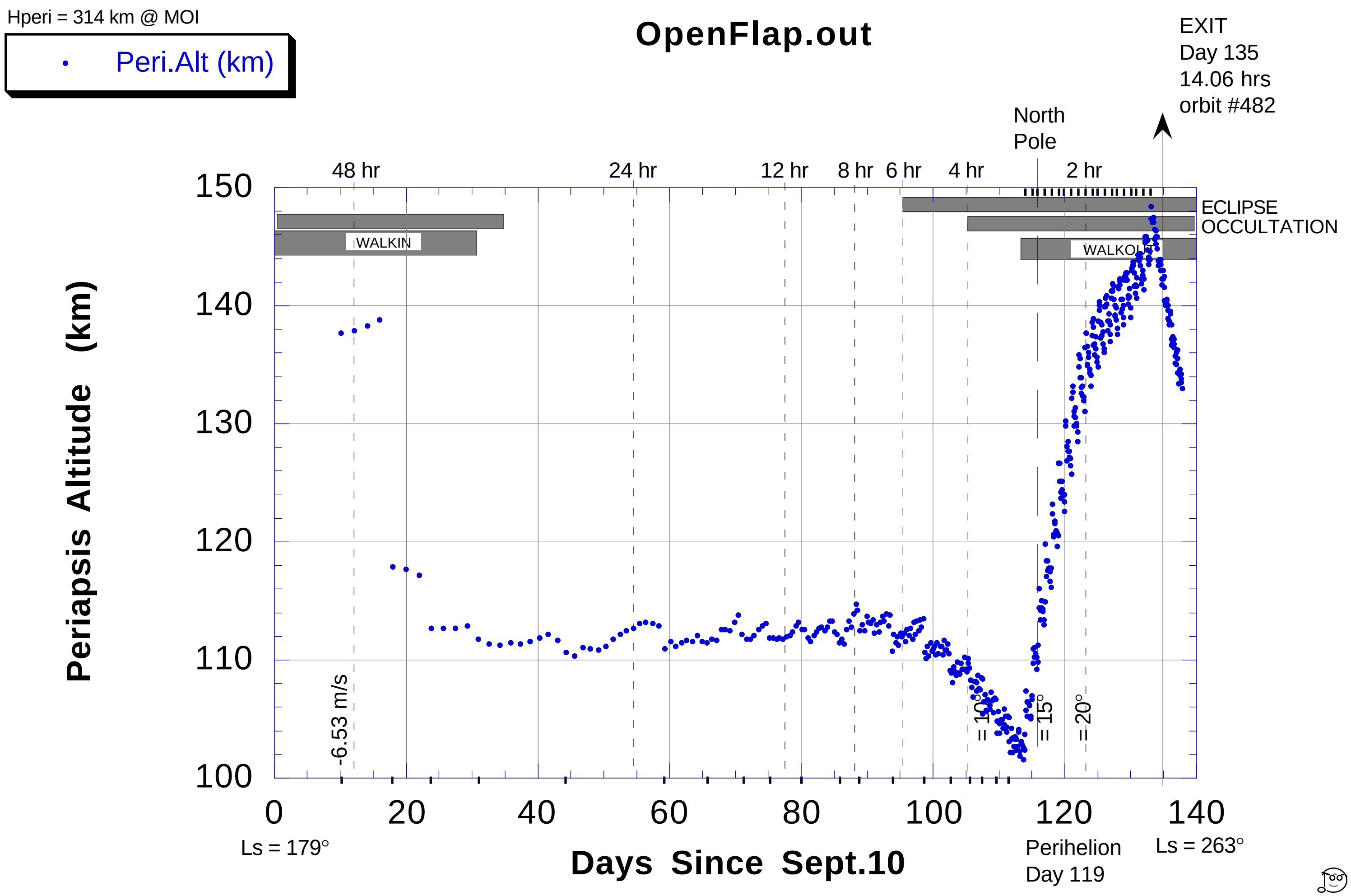


Figure 3.5 Altitude At Periapsis

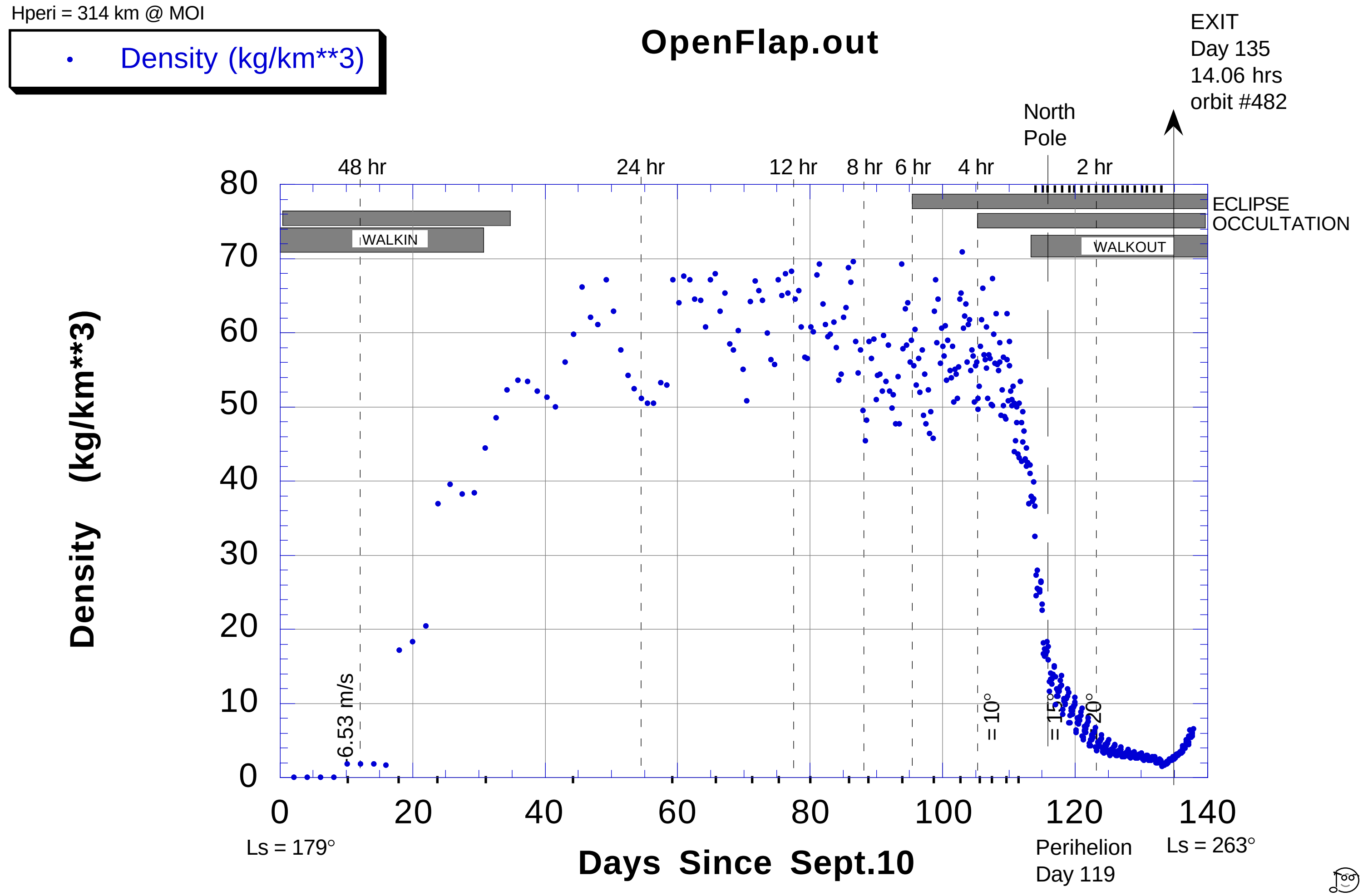


Figure 3.6 Atmospheric Density At Periapsis

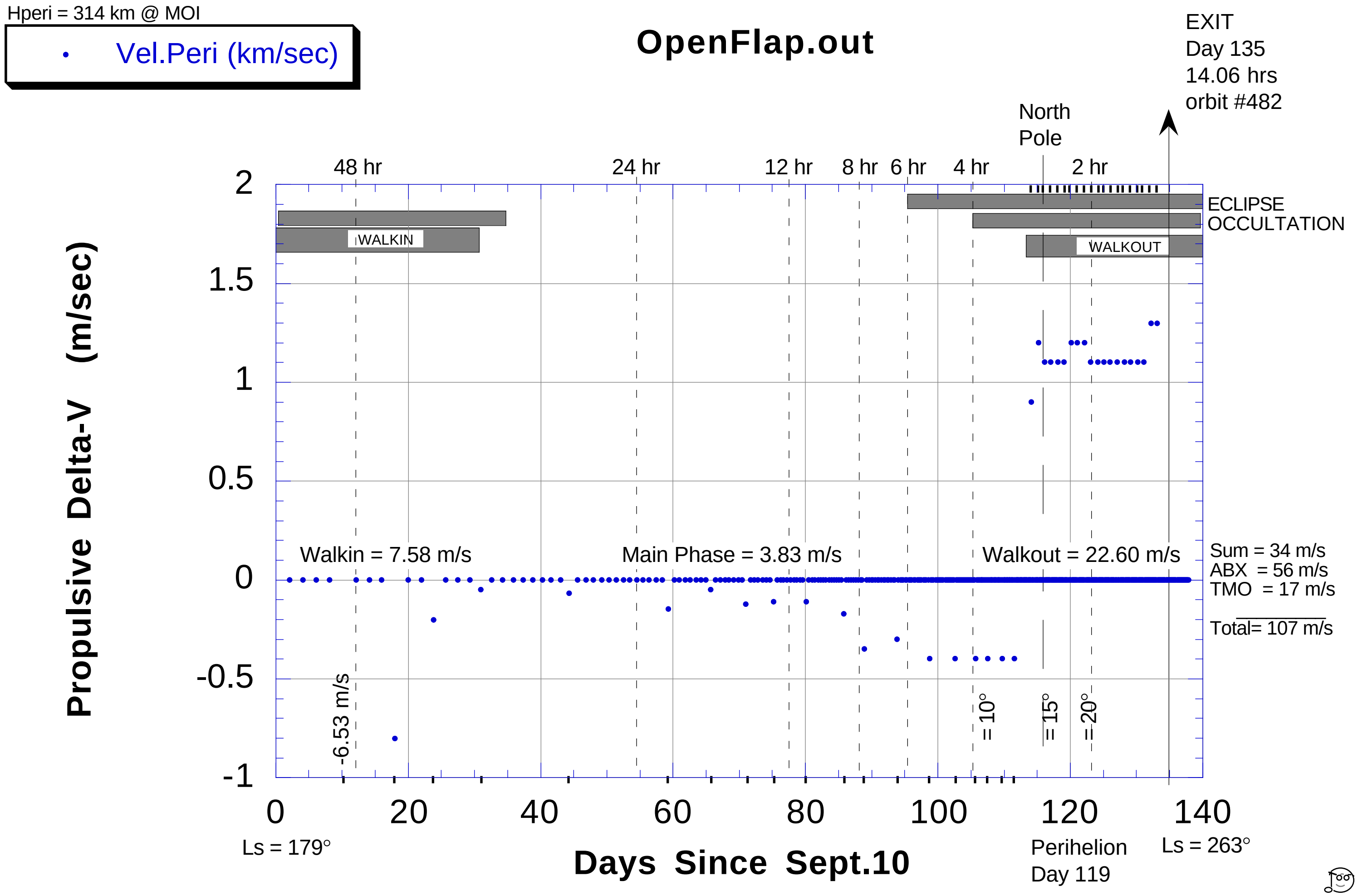


Figure 3.7 Propulsive Maneuvers: Frequency and Magnitude

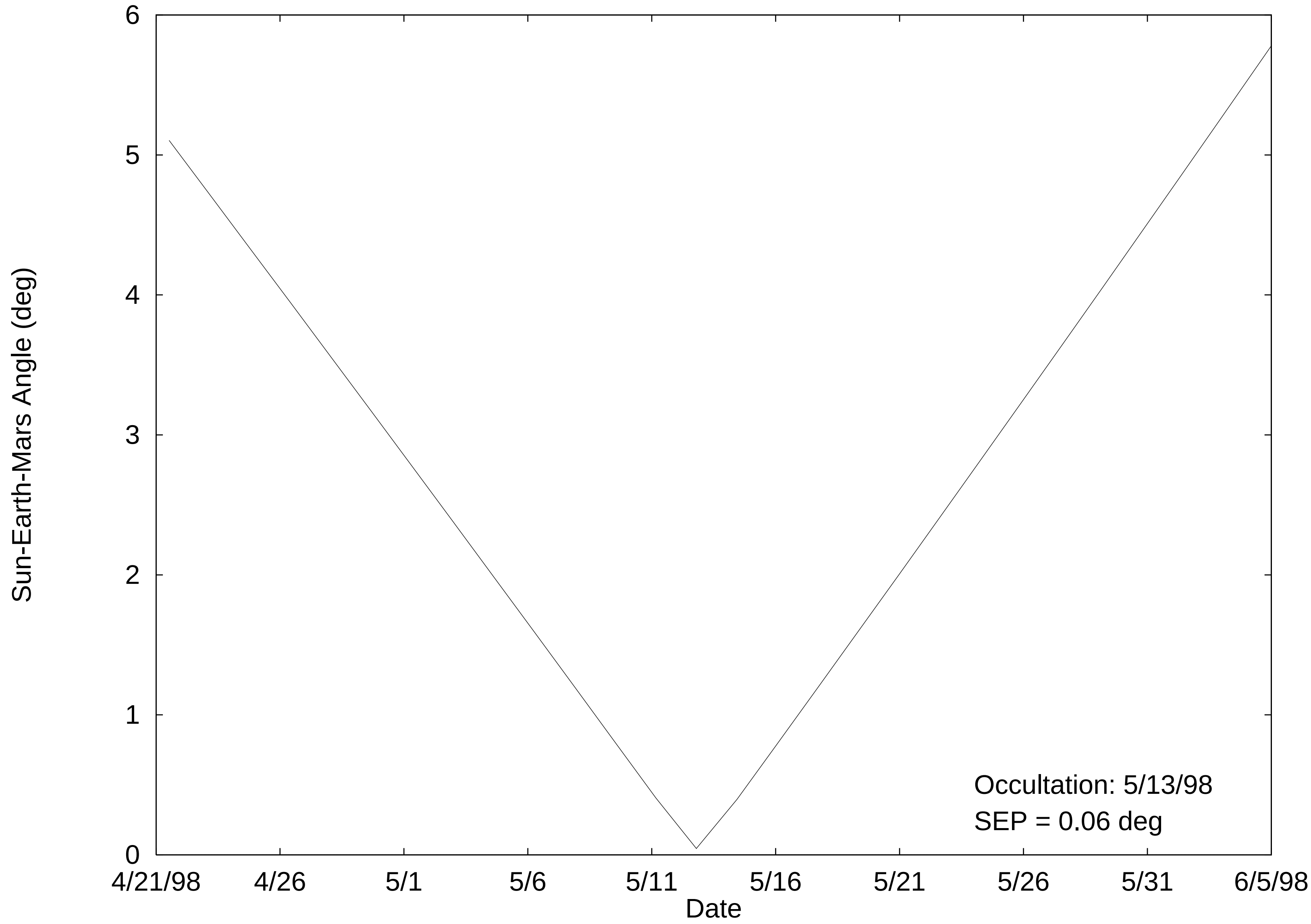


Figure 3.8 Mars Solar Conjunction (5/13/98) , SEP Angular Variation

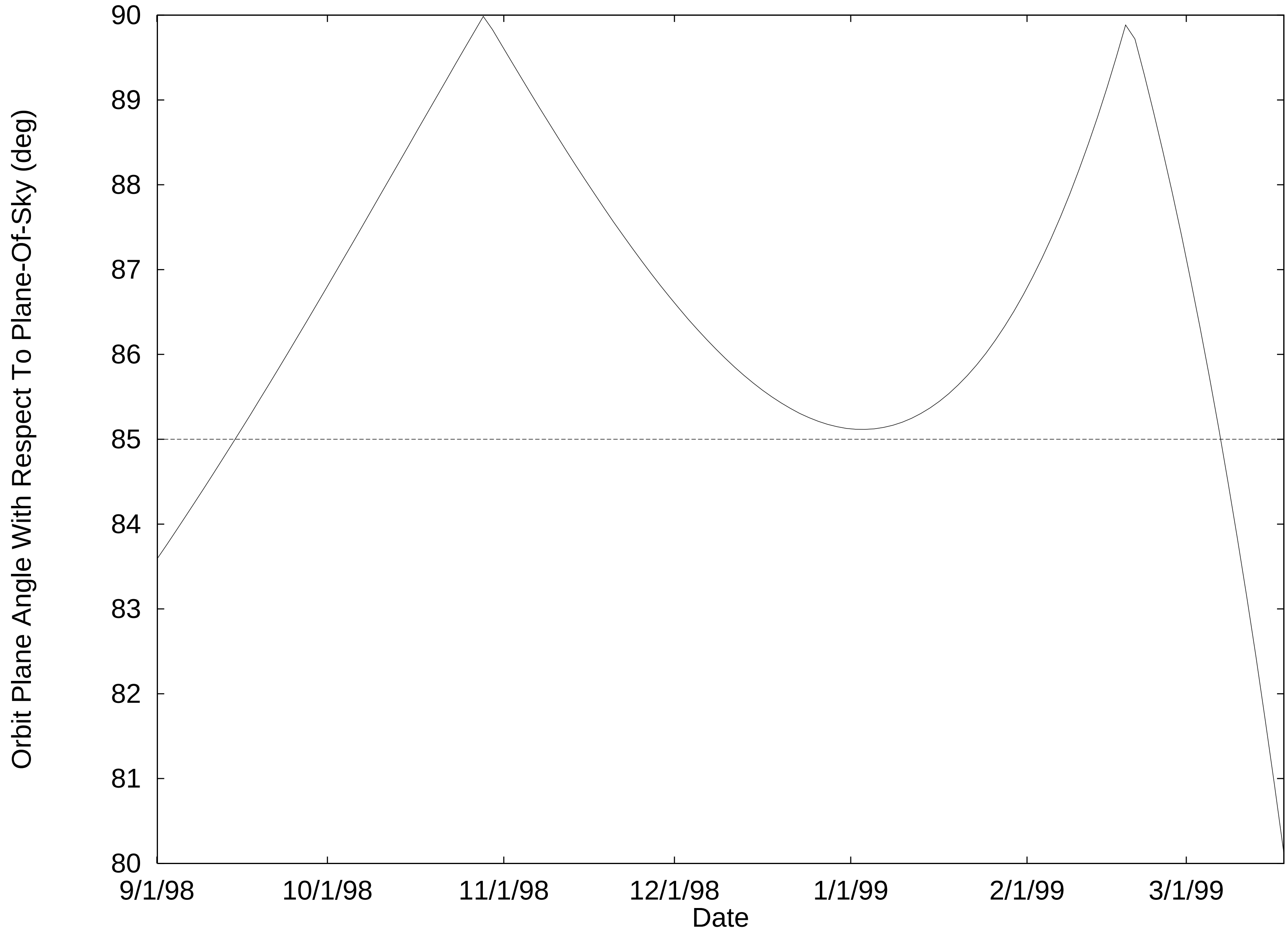


Figure 3.9 Orbit Plane Variation (I_{pos}) Throughout Mapping

4. RADIOMETRIC DATA AND NAVIGATION MODELS

The radiometric data used to navigate the spacecraft during the interplanetary phase consists of two-way coherent doppler (generally called range-rate) and round-trip, travel-time (generally called range) measurements. During the orbital phase, differenced doppler (i.e. the simultaneous acquisition of two-way and three-way doppler) will also be utilized for OD. This data shall be used during aerobraking and when the MGS orbit is in an edge-on configuration as seen from earth. During those times when only a down-link is possible, the usage of one-way doppler for OD is being investigated. This may be especially important during aerobraking as the spacecraft goes through periapsis.

4.1 NAVIGATION DATA AND ACCURACY

The data types required by navigation along with their end-to-end accuracy are summarized in Table 4.1.

TABLE 4.1 NAVIGATION TRACKING DATA

Data	Accuracy (1 σ)
Two-way coherent Doppler (60 s), mm/s	0.20 *
Round-trip travel time or range, meters	5.0 **
Differenced Doppler (60 s), mm/s	0.06

* 0.2 mm/s (range-rate) = 0.0112 Hz (X-band, two-way Doppler)
** 5 m (SRA range) = 35.05 range units (travel- time measurement)

4.1.1 SOLAR CONJUNCTION - DEGRADATION OF DOPPLER DATA

Representative doppler degradation results, acquired during Magellan's solar conjunction on 11/02/90, are shown in Fig. 4.1. Similar doppler degradation will be experienced by MGS during its solar conjunction on 5/13/98.

Fig. 4.1 Magellan doppler degradation due to solar conjunction.

4.1.2 STATION LOCATIONS AND ACCURACY

The station location accuracy for the DSN high efficiency stations (DSS 15, 45 and 65) provided to the Mars Observer Project (Ref. 4.1) are summarized in Table 4.2.

TABLE 4.2 TRACKING STATION ACCURACY

Cylindrical Coordinate	Accuracy (1 σ)
Longitude (m) (equivalent distance)	0.23
Distance from spin axis, Rs (m)	0.18
Distance perpendicular to earth's equatorial plane, Z (m)	0.23

The MGS Project will primarily use the 34-m HEF stations for commanding, telemetry and tracking data acquisition. Station coordinates are provided in Appendix 9.6. In addition, some DSN coverage will utilize beam-wave guide (BWG) antennas. These sites are expected to be flight operational for X-band uplink on these dates (Ref. 4.2) : DSS-25 (6/6/97), DSS-34 (8/2/97) and DSS-54 (10/1/97).

4.1.3 DATA CALIBRATIONS

Calibrations made to the radio tracking data are due to the following phenomena: a) earth's troposphere, b) earth's ionosphere, c) tracking station correction to the range, d) spacecraft correction to the range and e) interplanetary medium as necessary. The latter correction is important during solar conjunction and, at the same time, is also diminished by the usage of the X-band frequency (uplink transmitted frequency = 7150-7190 MHz; downlink frequency = 880∗f (uplink) / 749 MHz).
During flight operations, these calibrations shall be provided weekly by DSN operations.

4.2 NAVIGATION MODELS AND A PRIORI UNCERTAINTIES

The purpose of this section is to present a status of all error sources that affect navigation planning and flight operations.

4.2.1 PLANETARY AND SATELLITE EPHEMERIDES

During the interplanetary phase, an important error source is that associated with the location of the target, Mars. Both the nominal position of all the planets and the uncertainties associated with Mars and the earth-moon system have been provided in Ref. 4.3. These uncertainties at the MGS encounter are given in Appendix 9.3. The current development ephemeris (DE) used during navigation planning is DE-402; prior to flight operations, this shall be replaced with DE-403.

In addition to the planetary ephemeris, we also require ephemerides for the martian satellites Phobos and Deimos (Ref. 4.4).

4.2.2 ASTRODYNAMIC MODELS

During injection, a modest gravity field model for the earth and moon shall be used for navigation analysis. The source of these models are given in Refs. 4.5 and 4.6.

Throughout the interplanetary phase, the solar radiation pressure (SRP) force is the major perturbation acting on the spacecraft. Because of this, an interface has been established with LMA to provide accurate a priori inputs to this model. These consist primarily of the spacecraft's mass, major component areas, reflectivity coefficients and attitude throughout the mission. With respect to attitude during the interplanetary phase, the current plan is to have the spacecraft off-pointed approximately 60 deg (initially and then varying with time) from the sun-line (inner cruise). Thereafter, the spacecraft's X-axis will be earth pointed (outer cruise). Throughout cruise, the nominal spacecraft's spin rate will be 0.01 rpm (Ref. 4.7). Spacecraft configurations are shown in Appendix 9.2 and a simplified SRP model, used during planning, is given in Appendix 9.7.

4.2.3 SPACECRAFT OPERATIONAL CHARACTERISTICS

For Mars Observer, attitude was maintained by Reaction Wheel Assemblies (RWA). When a RWA was approaching a threshold or limit, angular momentum desaturation (AMD) occurred. The tendency of the spacecraft to rotate was controlled by hydrazine engine thrusting. The MO experience was that ninety AMDs occurred during cruise (almost two AMDs per week). Each imparted an effective velocity perturbation to the spacecraft of 1 mm/s on average. Each of these was modeled by a priori information and direct estimation from the doppler and range tracking data (Ref. 4.8).

For the MGS spacecraft, there are four rocket engine modules (REM) for a total of twelve 4.45 N thrusters. During the interplanetary phase, the AMDs (yaw unloads) will occur every 2.2 days during inner cruise and every 4.6 days during outer cruise. Each AMD will impart an effective velocity-change of 14 mm/s to the spacecraft. Spin unloads are less frequent and shall occur every 14 days.

Residual non-gravitational accelerations, due either to short-term,non-nominal spacecraft attitude or low-level, anomalous acceleration, shall be modeled as constant accelerations.

4.2.4 MARS GRAVITATIONAL FIELD

The gravitational field of Mars used in this design, called GMM-1, is contained in Ref. 4.9 and given in Appendix 9.5. This field and the corresponding uncertainties had been adopted for MO orbital operations and were carried over to the MGS navigation analysis. The original data, from which the field was developed, was the doppler tracking data acquired by the Mariner 9 and Vikings 1 and 2 missions. Note that these data do not provide a detailed sampling of the polar regions because of the geometry of the satellite orbits.

Recently another gravity field model, called JPL MARS 50C, has been published (Ref. 4.10). It appears to be a more accurate representation of Mars' gravity although it has been derived from almost the same data set as the GMM-1. Some additional data have been utilized in the analysis as explained in the reference. It is very likely that the Navigation Team will adopt this model for flight operations.

Figs. 4.2 and 4.3 show the uncertainty (one sigma) of each gravity coefficient of the respective models plotted on the same scale. Along the independent variable axis is each coefficient of a truncated 36x36 model in this order: J2, C21, S21, C22, S22, J3, C31, S31, ... As shown, the “ formal error” of the MARS 50C model appears smaller than the corresponding GMM-1 coefficients.

Fig. 4.2 Mars gravity field, GMM-1, uncertainties
Fig. 4.3 Mars gravity field, JPL MARS 50C , uncertainties

4.2.5 MARS ATMOSPHERIC DENSITY

During the aerobraking mainphase, the spacecraft's altitude at periapsis varies between 102 -112 km. Because of this low altitude, we acquired Mars atmospheric density software called MARS GRAM (Mars Global Reference Atmospheric Model). This software provides the current best engineering model atmosphere of Mars (Refs. 4.11 and 4.12) at the AB altitudes. Our primary interest is to generate a mean atmospheric density as a function of longitude, latitude, altitude and time. Also a measure of uncertainty and variation of density (over an orbital period) is needed. This information shall be used during planning and flight operations to analyze the tracking data and predict the orbital evolution of the spacecraft and the related uncertainties.
A nominal set of atmospheric densities used in this analysis is given in Section 5 and in Appendix 9.8.

Another important influence of the atmospheric density occurs when the spacecraft is in the mapping orbit. Although the density is significantly reduced with respect to AB, it is important for long-term (greater than one week) predictions of the spacecraft's location. This is especially true when Mars is near perihelion. Near aphelion, there is a strong reduction in density. This information is based upon Refs. 4.13 and 4.14; this model has been converted to software and shall be utilized during flight operations. The information contained in Appendix 9.9 provides an overview of the atmospheric density, its variation and uncertainty throughout the mapping phase.

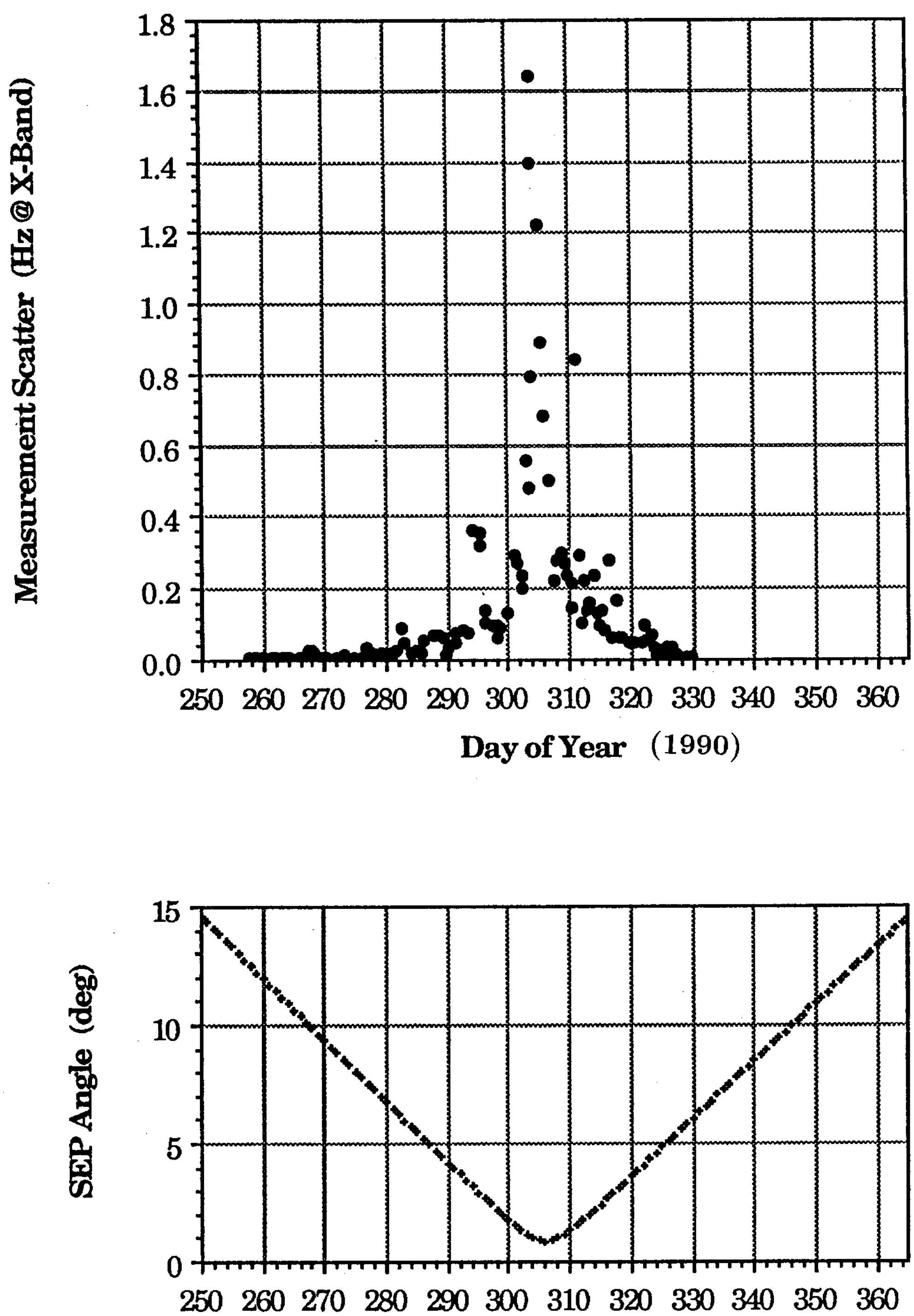


Fig 4.1 Magellan Doppler (CT= 60 s) Degradation Due To Solar Conjunction

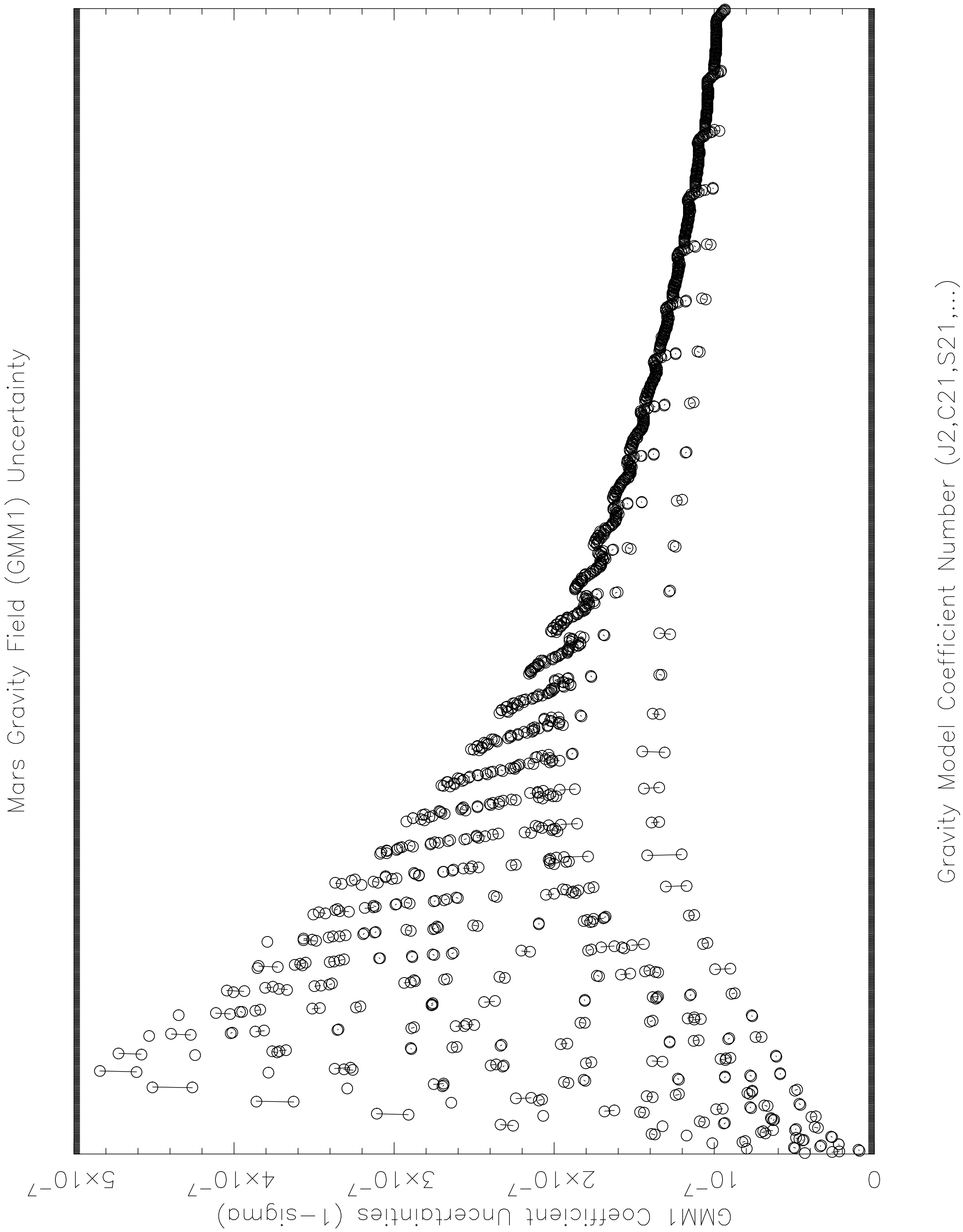


Fig 4.2 Mars Gravity Field, GMM-1, Uncertainty

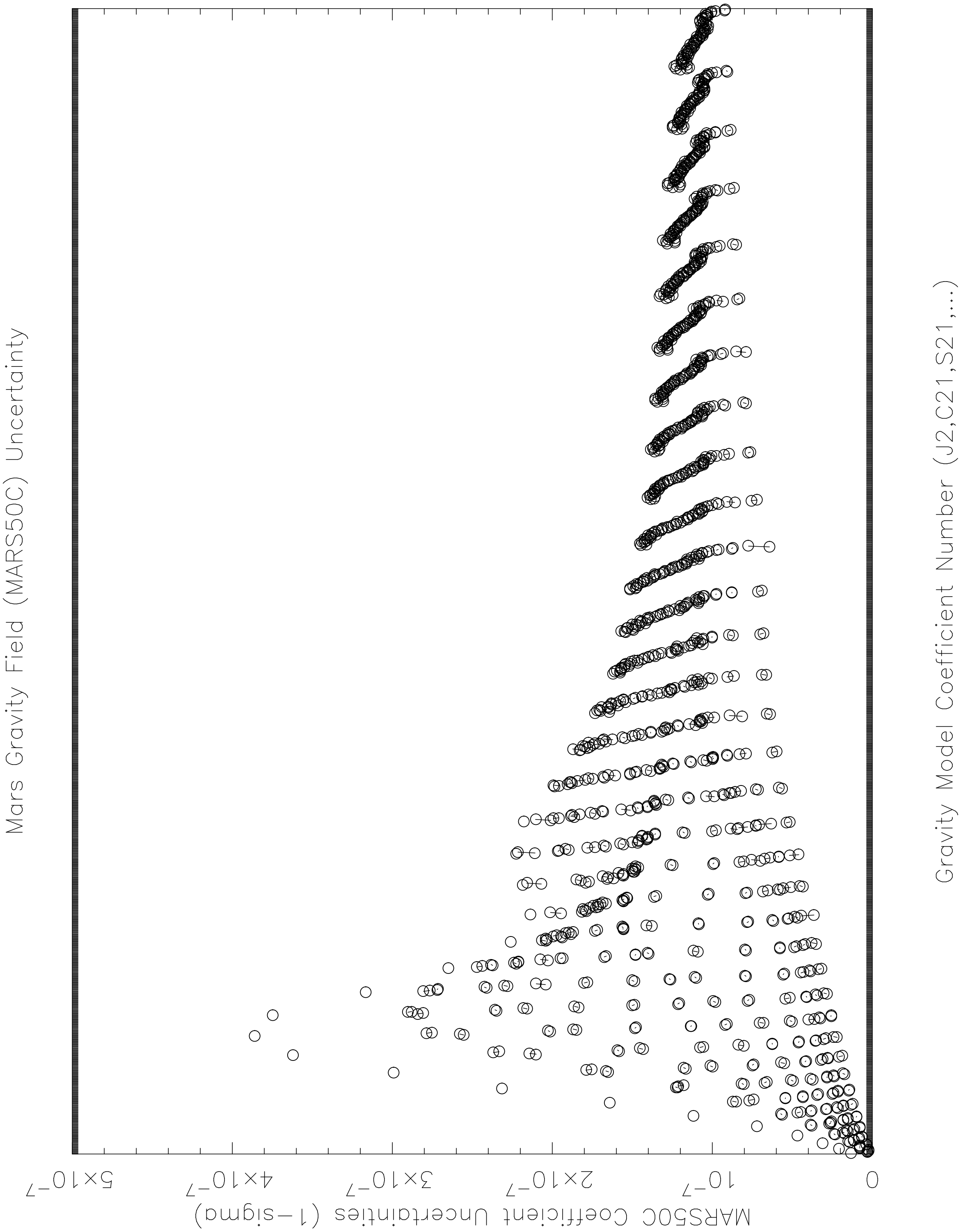


Fig 4.3 Mars Gravity Field, JPL MARS 50C, Uncertainties

5. ORBIT DETERMINATION ANALYSIS

This section describes the strategy used to acquire and analyze radiometric data for navigating the Mars Global Surveyor spacecraft.

5.1 INITIAL ACQUISITION: SPACECRAFT LOCATION UNCERTAINTY

The purpose of this section is to determine the spacecraft's positional accuracy immediately after injection and acquisition of the first tracking data by the DSN. During flight operations, these results shall be used to make a rapid assessment of the injection accuracy and to provide the DSN with angular pointing and received frequency predictions for the spacecraft.

One case was analyzed for the 11/6/96 launch date (Epoch = TECO (Third Stage Engine Cut-off) = 11/6/96, 17:57:46 ET (93 degree azimuth)). Note that TIP occurs at 8.6 minutes after TECO. It was assumed that tracking data would not be acquired until one hour after the above epoch; thereafter two hours of data were simulated (two-way coherent doppler and range). Uncertainties for geocentric angles (i. e. right ascension and declination) were generated for one and six hours after the data acquisition (also two and seven hours for the one hour data arc shown below). The angular results (in degrees) are summarized as follows:

Prediction Time	Right Ascension (1σ)	Declination (1σ)	Comment
11/6, 21:55:00	0.0036	0.00043	2 hr data arc
	0.057	0.0045	1 hr data arc
11/7, 02:55:00	0.0037	0.00086	2 hr data arc
	0.059	0.0037	1 hr data arc

5.2 INTERPLANETARY PHASE

Based upon a nominal interplanetary trajectory, simulated tracking data were generated and OD analyses were performed throughout this phase of the mission. The strategy involved analysis of n days of simulated data to determine trajectory initial conditions (position and velocity) at epoch and estimates of various model parameters along with their corresponding uncertainties. These uncertainties were then mapped to encounter and displayed in a target coordinate system (Appendix 9.4) in order to assess Navigation's ability to deliver the spacecraft to a specific location at a specific time. During flight operations, the propulsive maneuver design shall be based upon the operationally-determined flight path of the spacecraft and the associated targeting errors.

The current time-placement of the TCMs (Trajectory Correction Maneuvers) is shown in Table 5.1.

TABLE 5.1 TCM SCHEDULE FOR THE FIRST AND LAST LAUNCH / INJECTION DATES

EVENT	EPOCH	INTERVAL (DAYS)
INJECTION (I)	11/06/96	--
TCM-1 (I+15)	11/21/96	15
TCM-2 (TCM-1 + 120)	03/21/97	120
TCM-3 (TCM-2 + 30)	04/20/97	30
TCM-4 (E - 20)	08/22/97	124
ENCOUNTER (E)	09/11/97	20
		309
INJECTION (I)	11/25/96	--
TCM-1 (I+15)	12/10/96	15
TCM-2 (TCM-1 + 105)	03/25/97	105
TCM-3 (TCM-2 + 30)	04/24/97	30
TCM-4 (E - 20)	09/02/97	130
ENCOUNTER (E)	09/22/97	20
		300

5.2.1 ORBIT DETERMINATION RESULTS FOR TRAJECTORY CORRECTION MANEUVERS AND THE MARS ORBIT INSERTION MANEUVER

In order to prepare for the design and execution of a TCM, OD uncertainties were evaluated by simulating at least three solutions: 1) estimate only the spacecraft's initial position and velocity at epoch, 2) estimate the state and the three SRP coefficients and 3) estimate the state, SRP coefficients and three components of a constant, non-gravitational force model (Appendix 9.7). In all cases, uncertainties associated with the following models were considered (if model parameters are estimated then they are not considered): three-component SRP, three-component constant acceleration, DSN station locations, and earth-Mars ephemeris. For the near-earth phase, we accounted for uncertainties associated with a modest earth and lunar gravity field. For propagating uncertainties to Mars, a two-parameter Mars gravity field model (GM and the oblateness) was considered. A priori uncertainties have been previously summarized in Section 4. In an on going analysis, some of these uncertainties are being varied in order to estimate their impact on the OD uncertainties. In addition, we have varied the data set.

The X-band tracking data accuracy assumptions are: 1) two-way coherent doppler noise is 0.2 mm/s (60 s average) which equals 0.0112 Hz, and 2) SRA range noise is nominally 35.05 range units (RU) or 5 m. Note that the doppler uncertainty is scaled according to the doppler count-time, CT:

$$\sigma \text{ (doppler) } = \sigma \text{ (apriori) } [\, 60/CT \text{ (s) }]^{1/2}.$$

The analysis procedure follows this format:

a) Simulate tracking data according to the baseline data acquisition plan (Ref 5.1).

b) Assume a realistic assessment of data quality.

c) Develop equations of motion for the spacecraft including all necessary models which will influence the spacecraft's motion and trajectory. Also account for the uncertainties associated with the target's state and with the data acquisition site. As necessary evaluate data quality degradation due to the earth's atmosphere and the interplanetary medium.

d) Integrate the equations of motion from epoch to encounter, analyze the simulated data and determine the covariance of the spacecraft's state at epoch. Propagate these errors from epoch to encounter or some future time and display them in a variety of coordinates and coodinate systems.

e) Repeat this process for each of the TCMs. During flight operations, long and short data arcs shall be evaluated in order to provide a cross-check on the OD results.

The results of this analysis are summarized in Tables 5.2 (see also Fig. 5.1) and 5.3.

Fig. 5.1 Spacecraft target uncertainties for TCM execution, 11/06/96 launch.

TABLE 5.2 OD RESULTS FOR TCM DESIGN
FIRST LAUNCH DATE, 11/06/96

Maneuver (Data Arc)	Parameters Estimated	B-Plane Error Ellipse (one sigma) SMAA (km)	SMIA (km)	θ (deg)	LTOF (s)
TCM-1 (5 Days)	State	1124	208	171	1277
TCM-2 (75 Days)	State, SRP, NG	426	189	178	150
TCM-3 (106 Days)	State, SRP, NG	322	166	179	95
TCM-4 (281 Days)	State, SRP, NG (stochastic)	32	12	107	5
MOI (185 Days)	State. SRP, NG (stochastic)	31	10	106	5

1. In all of these analyses, doppler and range data were simulated and weighted at 0.2, mm/s (60 s average) and 5 m respectively.
2. See Appendix 9.4 for the B-plane definition.
3. These results are consistent with an older encounter target and a previous TCM schedule. In addition, current information is now available to assess the influence of MGS AMDs. Thus an update of these results is in progress.
4. The current encounter target coordinates (with respect to the Mars mean equator of date) are:

Encounter (ET)	9/11/97, 01:27:53
B.T (km)	-395.7
B.R (km)	-7278.3
Theta (deg)	-93.1
Rp (km)	3785. (unbraked)

TABLE 5.3 OD RESULTS FOR TCM DESIGN
LAST LAUNCH DATE, 11/25/96

		B-Plane Error Ellipse (one sigma)			
Maneuver (Data Arc)	Parameters Estimated	SMAA (km)	SMIA (km)	θ (deg)	LTOF (s)
TCM-1 (5 Days)	State	1530	224	17.6	1105
TCM-2 (54 Days)	State, SRP, NG	399	181	7.5	107
TCM-3 (85 Days)	State, SRP, NG	414	166	178	75
TCM-4 (271 Days)	State, SRP, NG (stochastic)	34	10	105	5
MOI (196 Days)	State, SRP, NG (stochastic)	28	8	102	5

1. In all of these analyses doppler and range data were simulated and weighted at 0.2 mm/s (60 s average) and 5 m respectively.
2. See Appendix 9.4 for the B-plane definition.
3. These results are consistent with an older encounter target and a previous TCM schedule. In addition, current information is now available to assess the influence of MGS AMDs. Thus an update of these results is in progress.

4. The current encounter target coordinates (with respect to the Mars mean equator of date) are:

Encounter (ET)	9/22/97, 01:10:01
B.T (km)	-433.0
B.R (km)	-7251.3
Theta (deg)	-93.4
Rp (km)	3785. (unbraked)

5.2.1.1 SPACECRAFT LOCATION: KNOWLEDGE AND PREDICTION

This section provides representative spacecraft location accuracy (knowledge and prediction) during the interplanetary phase. Since the spacecraft's ephemerides (based on SPK files) will be transmitted to the spacecraft at periodic intervals, the accuracy of the prediction will be factored into the frequency of the transmission. Representative results for one segment of the interplanetary phase are given in Table 5.4.

TABLE 5.4 SPACECRAFT'S GEOCENTRIC AND HELIOCENTRIC POSITION ACCURACY (ONE SIGMA)

Date	σR (km)	$\sigma\phi$ ($\times 10^{-4}$ deg)	$\sigma\theta$ ($\times 10^{-4}$ deg)	Comment
11/06/96	--	--	--	Initial epoch
1/18/97				
Geocentric	0.005	0.016	0.039	End of 74 day
Heliocentric	0.7	0.025	0.026	data arc
2/01/97				
Geocentric	1.2	0.037	0.049	2 week
Heliocentric	1.4	0.025	0.026	prediction
2/15/97				
Geocentric	4.7	0.11	0.11	4 week
Heliocentric	4.7	0.030	0.029	prediction
3/15/97				
Geocentric	19.6	0.25	0.24	8 week
Heliocentric	19.5	0.058	0.059	prediction

Geocentric: geocentric inertial coordinates referenced to the earth's mean equator of date (ϕ = right ascension ; θ = declination).
Heliocentric: heliocentric inertial coordinates referenced to the sun's mean equator of date (celestial longitude ; celestial latitude).
Uncertainties do not account for propulsive maneuver execution errors

5.2.1.2 ENCOUNTER TARGET OR AIMPOINT : PERIAPSIS ALTITUDE

As a result of the project's evaluation of delta-V requirements as stated in the MRD and Mission Plan, navigation evaluated a revised Mars target. The current post-MOI capture orbit is targeted to a 314. km periapsis altitude. Based on future analysis, this may be revised to 250. km.

5.3 ORBIT INSERTION AND AEROBRAKING PHASE

The purpose of this section is to provide an estimate of OD uncertainty during the orbit insertion phase which includes aerobraking (AB) and the gravity calibration (GC) period. In order to assess OD uncertainty throughout this phase, we simulated radiometric data using the initial conditions and epochs given in Table 5.5 (capture orbit and first 78% of AB main phase) and Table 5.6 (for the remaining AB main phase) .

TABLE 5.5 ORBIT PARAMETERS AND DENSITY MODEL ORBIT INSERTION AND AEROBRAKING MAIN PHASE

Epoch (ET)	09/11/97 06:56:03	10/10/97 23:05:00	11/02/97 11:44:00	11/30/97 20:52:00
Tp (P1)	09/13/97 00:59:43	10/12/97 14:40:21	11/03/97 11:31:08	12/01/97 06:30:35
Period (hrs)	48.0	40.0	24.0	10.0
Altitude (km	314.5	111.40	112.725	112.38
Latitude (deg)	32.5	34.76	37.21	44.20
a(km)	31753.9	28070.8	20046.7	11215.7
e	0.883	0.875	0.8254	0.688
Ω (deg)	-41.378	-41.192	-40.920	-40.199
I (deg)	92.85	92.826	92.789	92.836
ω (deg)	147.461	145.191	142.737	135.73
TA (deg)	0.0	0.0	0.0	0.0
Rp (km)	3702.8	3499.0	3499.6	3497.2
Simulation For	AB-1	AB	AB	AB
THREE PARAMETER, STATIC, ATMOSPHERIC DENSITY MODEL				
ρ_o (x 10^{-05} g/m^3)	---	4.855	5.12	6.105
h_o (km)	---	111.40	112.728	112.383
H (km)	---	9.05	9.17	9.14
70% ρ_o (x 10^{-05} g/m^3)	---	3.398	3.585	4.273

Coordinate system: Mars centered, Mars mean equator and IAU vector of epoch

TABLE 5.6 ORBIT PARAMETERS AND DENSITY MODEL AEROBRAKING MAIN PHASE

Epoch (ET)	12/14/97 20:50:56	12/29/97 00:59:45	01/01/98 23:33:28
Tp (P1)	12/15/97 02:21:58	12/29/97 03:31:15	01/02/98 01:28:23
Period (Hrs)	6.0	3.0	2.42
Altitude (km)	112.62	103.77	107.36
Latitude (deg)	52.29	72.01	83.57
a (km)	7931.9	5014.8	4322.3
e	0.559	0.306	0.194
Ω (deg)	-39.373	-37.405	-36.310
I (deg)	92.788	92.752	92.700
ω (deg)	127.62	107.78	95.831
THREE PARAMETER, STATIC, ATMOSPHERIC DENSITY MODEL			
ρ_o (x 10^{-05} g/m^3)	5.295	5.878	2.460
h_o (km)	112.615	103.761	107.347
H (km)	9.01	7.58	7.24
70% ρ_o (x 10^{-05} g/m^3)	3.706	4.115	1.722

Coordinate system: Mars centered, Mars mean equator and IAU vector of epoch

5.3.1 ORBITAL ANALYSIS FOR FIRST WALKIN MANEUVER, AB-1

One orbit, immediately after the MOI burn, was simulated (48 hours of doppler data) in order to prepare for the AB-1 maneuver. After analysis, the OD results were propagated for seven days or 3.5 orbits to the fifth apoapsis and are given in Table 5.7. This maneuver shall lower the periapsis altitude from 314. km to 138. km. (This has recently been revised to 150. km.)

TABLE 5.7 OD UNCERTAINTY FOR AB-1 PLANNING

Epoch	Predicted Position Accuracy (km, 1σ) Downtrack	Crosstrack	Radial	Comment
9/10/97	---	---	---	hp = 314. km
9/20/97	1.14	0.42	0.37	A5 ; 7 day prediction

Note : AMDs during the propagation interval need to be reviewed.
This analysis is based on the old 11/3/96 launch date.

5.3.2 ACCURACY OF ATMOSPHERIC DENSITY DETERMINATION DURING WALKIN

One case was analyzed immediately after the AB-1 propulsive maneuver which lowers the periapsis altitude to 138. km. (This has recently been revised to 150. km. This orbit is now similar to the one after AB-2.) Orbital parameters, the three-parameter density model and atmospheric drag perturbations are given in Table 5.8. A graphic overview of the tracking data acquisition and analysis strategy are given in Fig. 5.2 and data weights, estimated and consider parameters, etc. for two representative cases are given in Appendix 9.10. A summary of this information is provided in Table 5.9 along with the result that the reference density (ρ_o) can be determined to 13.1% (1σ) or to 5.6% (1σ) . For the former result, orbital perturbations due to spacecraft thrusting around periapsis were estimated in the OD process. For the latter result, spacecraft thrusting was assumed to be modeled independently and accurately from telemetry data; thus they were not estimated in the OD process. As indicated, we have fixed the value of the ballistic coefficient. In addition, we have assessed the duration of the drag pass, from the viewpoint of a sensible acceleration or effective velocity perturbation to be eight minutes centered on periapsis. LMA aerobraking designers would like a 10% (3σ) determination of atmospheric density. Lowering the periapsis altitude by an additional 5-10 km (as a result of AB-1) would give a nominal density of 4.0 kg/km^3 (see Fig. 5.3). Assuming $\sigma\,\rho_o$ = 0.20 kg/km^3 with ρ_o = 4.0 kg/km^3 gives a one-sigma uncertainty of 5%.

TABLE 5.8 ORBIT PARAMETERS AND DENSITY MODEL AEROBRAKING WALKIN PHASE

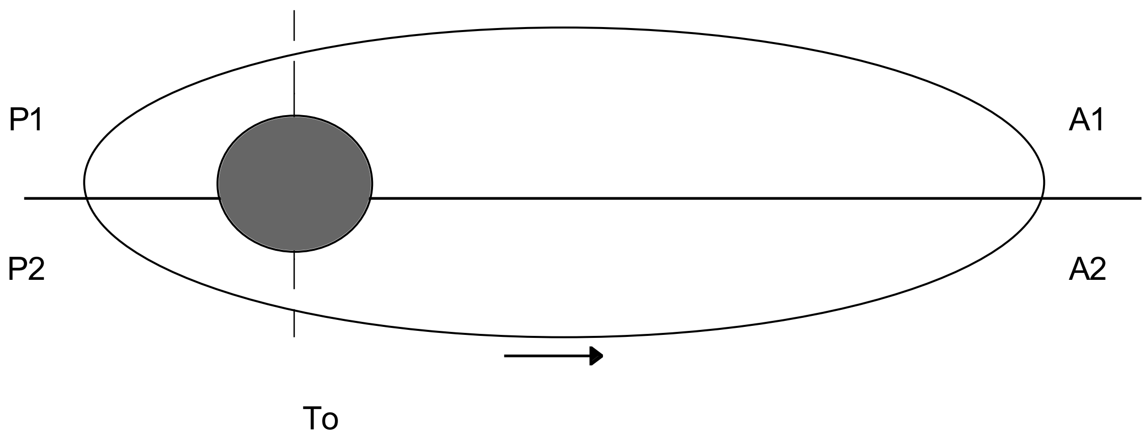
Epoch (ET)	09/20/97 02:07:00	OTHER CONSTANTS Quantity	Value
Tp (P1)	09/22/97 01:24:54		
Period (Hrs)	48.0	Mass (kg)	745.
Altitude (km)	137.878	Cd	1.95
Latitude (deg)	33.14	Area (m^2)	17.04
a (km)	31891.2	$\frac{M}{Cd*A}$	22.42 kg/m^2
e	0.88944		
Ω (deg)	-41.353	Due to atmospheric drag :	
I (deg)	92.826	ΔP (s)	231.1
ω (deg)	146.813	Δa (km)	28.5
TA (deg)	0.0	Δe	0.00010
Rp (km)	3525.968	ΔRa (km)	57.0
Simulation For	Density Determination	ΔV (m/s)	0.124

THREE PARAMETER, STATIC, ATMOSPHERIC DENSITY MODEL

ρ_o (x 10^{-06} g/m^3)	1.527
h_o (km)	137.879
H (km)	10.37
70% ρ_o (x 10^{-06} g/m^3)	1.069

Coordinate system: Mars centered, Mars mean equator and IAU vector of epoch

DENSITY DETERMINATION STRATEGY DURING WALKIN




```
                         D/L                                  U/L
I---------------I----------------I*I-------------------I-------------I*I--------------I

P    ± 0.5        4.0                      6.0            1.0             11.75     A
                        TIME INTERVAL *, HOURS
```

NO DATA — NAV DATA ACQUISITION — NAV ANALYSIS — GRD PREPARATION

PURPOSE : EVALUATE ACCURACY OF ATMOSPHERIC DENSITY AND PROVIDE PREDICTED Tp AND Rp FOR SPACECRAFT ENTRY INTO NEXT DRAG PASS (PERIAPSIS)

* TIME INTERVALS ARE APPROXIMATE

Fig. 5.2 Graphic representation of tracking data acquisition and orbit determination strategy (orbital period = 48 hours).

TABLE 5.9 ATMOSPHERIC DENSITY ACCURACY DETERMINATION

DOPPLER DATA, ERROR MODELS AND DENSITY RESULTS

DOPPLER DATA

ONE ORBIT PLUS 4.5 HOURS PAST P1; ALSO SIMULATE DATA TO A2.
NO DATA WITHIN 0.5 HOURS OF PERIAPSIS.
σ (DOPPLER) = 0.2 MM/S (60 S); ALSO USE 1.0 MM/S.

MODELS AND A PRIORI UNCERTAINTIES

MODEL	SOURCE / COMMENT
25 X 25 GMM-1	JGR, 98, 11/25/93
EXPONENTIAL DENSITY (3 PARAMETER)	MARSGRAM V 3.31 (ρ_o = 1.527 kg/km^3)
S/C REM THRUSTING AROUND PERIAPSIS	MAGELLAN OPERATIONS EFFECTIVE 15 MM/S UNCERTAINTY (1σ)
OTHER CONSIDERATIONS	
RESIDUAL ACCELERATION	MO OPERATIONS
SCALE HEIGHT UNCERTAINTY	1-2 KM OR FIX
GM UNCERTAINTY	σ = 0.0512 KM^3/S^2
BALLISTIC COEFFICIENT	FIXED

ESTIMATE

STATE, DENSITY, 4X4 GRAVITY FIELD AND PERIAPSIS THRUSTING PERTURBATION

CONSIDER

25 X 25 GRAVITY FIELD, RESIDUAL ACCELERATION ; (VARIABLE)

RESULTS

$\sigma\ \rho_o$ = 0.20 kg/km^3 OR 13.1 % ; DATA: 1 ORBIT (+4 HRS); 1.5 ORBITS.

$\sigma\ \rho_o$ = 0.086 kg/km^3 OR 5.6 % ; IF THRUSTING PERTURBATION CAN BE ACCURATELY MODELED VIA THE AMD INTERFACE (TELEMETRY).

DATA WITHIN P1+20 MIN TO P1+30 MIN (IF AVAILABLE) ONLY SLIGHTLY IMPROVES THE ESTIMATED DENSITY ACCURACY.

DRAG ACCELERATION EFFECTIVE WITHIN PERIAPSIS $\pm$ 3-4 MIN :

TIME	ACCELERATION (KM/S2)	DYN P (N/M2)
P1	7.93 X 10^{-7}	0.018
P1+3 MIN	0.10 X 10^{-7}	0.00022
P1+5 MIN	4.13 X 10^{-12}	---

Fig. 5.3 Nominal atmospheric density as a function of altitude.

The accuracy to which the time-of-periapsis-passage (Tp) can be predicted is summarized in the following table.

TABLE 5.10 NAVIGATION RESULTS FOR WALKIN

EPOCH AND ORBITAL PERIOD (HRS)	PERI- APSIS	PREDICTED UNCERTAINTIES Tp (s) (DENSITY VARIAT) 60%	90%	Rp (km ; 1 σ) GRAVITY	3X GRAVITY
09/20/97	P2	7.9	7.9 *	0.02	--
48.0	P3	124.7	187.1*	0.03	--

* Analytical estimation

5.3.3 ORBITAL ANALYSIS FOR THE MAIN PHASE OF AEROBRAKING

For the first 78% of mainphase aerobraking, we analyzed orbits having an orbital period of 40, 24 and 10 hours. During this time, the nominal plan is for continuous tracking data acquisition. However, we assumed no data could be acquired within 30 minutes of periapsis because of the spacecraft's aerobraking attitude precludes communication with the earth. The major parameters of interest are the radial distance (Rp) or altitude at periapsis and the time of periapsis passage (Tp). Uncertainties are required for both reconstruction and prediction. Tp and Rp predicted accuracies for these three cases are given in Table 5.11.

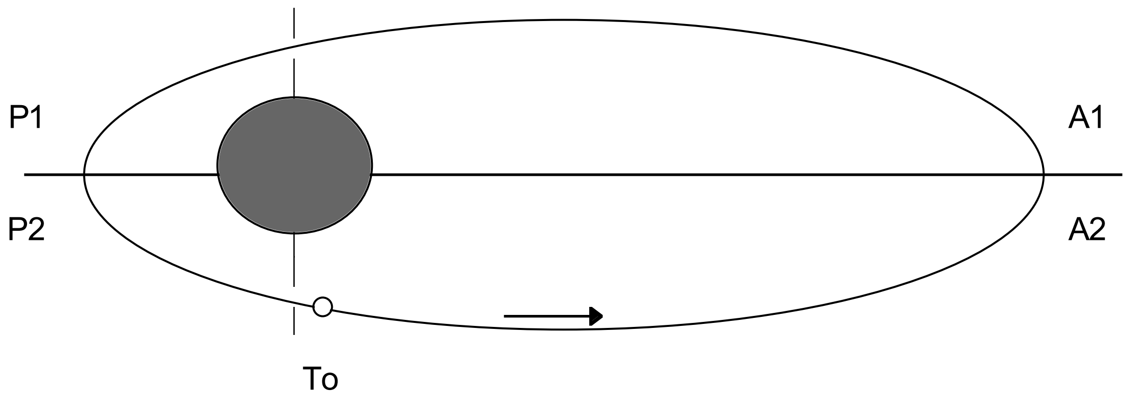
During flight operations, the Tp shall be uplinked to the spacecraft and used to prepare the spacecraft for entry into and out of the “drag pass”. Knowledge and control of Rp is necessary in order that the AB implementation proceed as designed. At periapsis, if the spacecraft dips too low into the atmosphere then there is a concern that spacecraft component heating could become a problem.

For these cases, the strategy for data acquisition and analysis is illustrated in Fig 5.4. To represents the epoch of the analysis after which

tracking data are acquired for one orbit plus 4.5 hours after periapsis. The post-periapsis data are primarily used to estimate atmospheric density model parameters. P1 signifies the first periapsis. Once these data are transferred from the DSN to the Navigation Team (via the DSN interface, OSCAR), six hours are required for analysis. The immediate results are predictions of future periapsis times (i. e. Tp2, Tp3, ...). This information is contained in two files called OPTG and SPK .
In addition, these results will be used monitor orbit-to-orbit density variations. The density information will be assembled into a database and will be valuable for modifying flight operations strategies (as necessary) during the latter stages of mainphase aerobraking.

For the remaining 22% of the main phase of AB, three cases were analyzed as shown in Table 5.6. The data acquisition and analysis strategy are similar to that previously described and the results are presented in Table 5.12. Note that multiple periapses predictions are possible for cases with orbital periods of 3.0 and 2.42 hours.

AEROBRAKING ORBIT DETERMINATION STRATEGY



D/L U/L

I---------------I----------------I*I--------------------I-------------I*I--------------I

P ± 0.5 4.0 6.0 1.0 7.75 A

TIME INTERVAL, HOURS

NO DATA	NAV DATA ACQUISITION	NAV ANALYSIS	GRD PREPARATION

PURPOSE : PROVIDE PREDICTED Tp AND Rp FOR SPACECRAFT ENTRY INTO NEXT DRAG PASS (PERIAPSIS).

Fig 5.4 Overview of Navigation orbit determination strategy during aerobraking (orbital period = 40 hours). Time durations are approximate.

TABLE 5.11 NAVIGATION RESULTS AND STRATEGY- FIRST 78 % OF AEROBRAKING MAIN PHASE

EPOCH AND ORBITAL PERIOD (HRS)	PERI- APSIS	PREDICTED UNCERTAINTIES Tp (s) (DENSITY VARIAT) 30%	60%	90%	Rp (km ; 1 σ) GRAVITY	3X GRAVITY
10/10/97	P2 *	5.6	5.6	5.6	0.021	0.062
40.0	P3	1260.	2369.	---	0.095	0.11
11/04/97	P2 *	1.9	1.9	1.9	0.07	0.20
24.0	P3	706.	1356.	---	0.10	0.21
11/30/97	P2 *	0.3	0.3	0.3	0.02	0.05
10.0	P3	163.	322.	481.	0.05	0.07
	P4	481.	949.	1420.	0.08	0.10

* NAV SHALL PREDICT ONE PERIAPSIS AHEAD TO SATISFY THE Tp ACCURACY REQUIREMENT (225 S).

NOTES

1. INTERVAL FROM START OF AB MAINPHASE (10/10/97) TO P = 6 HOURS (12/14/97) : 63 DAYS AND 102 ORBITS
2. THESE RESULTS DO NOT INCLUDE MANEUVER EXECUTION ERRORS
3. NAV IS USING A 70% DENSITY VARIATION OR UNCERTAINTY (2 σ) FOR Tp ACCURACY ESTIMATES (JPL ATMOSPHERIC DENSITY WORKSHOP, 3/22-23/95, REF 5.2)
4. THE ACCURACY OF THE Tp PREDICTION FOR THE SECOND PERIAPSIS PASSAGE IS WELL BELOW THE REQUIREMENT FOR ALL ASSUMED LEVELS OF ORBIT-TO-ORBIT DENSITY VARIATION.
5. THE DEGRADATION IN Tp ACCURACY FOR THE NEXT PERIAPSIS (P3) IS DUE TO THE LARGE CHANGE IN ORBITAL PERIOD PER ORBIT (ΔP) COUPLED WITH THE UNCERTAINTY IN THE DENSITY. FOR EXAMPLE, FOR THE 40 HOUR CASE, ΔP = 4200. S FOR THE NOMINAL DENSITY. IF AT P2 THE DENSITY CHANGES BY 30% THEN THE ΔP CHANGES BY 30% (1260. S) AND THE Tp WILL BE IN ERROR BY 1260. S . OTHER FACTORS ARE INVOLVED BUT DENSITY DOMINATES.

TABLE 5.12 NAVIGATION RESULTS AND STRATEGY- LAST 22 % OF AEROBRAKING MAIN PHASE

EPOCH AND ORBITAL PERIOD (HRS)	PERI- APSIS	PREDICTED UNCERTAINTIES Tp (s) (DENSITY VARIAT) 30%	60%	90%	Rp (km ; 1 σ) (60% DENSITY) GRAVITY	3X GRAVITY
12/14/97	P2	0.15	0.2	0.2	0.02	0.07
6.0	P3 *	67.2	130.	193.	0.03	0.08
	P4	196.	377.	562.	0.04	0.10
12/29/97	P4	21.	36.5	53.5	0.04	0.11
3.0	P5 *	60.7	109.	160.	0.06	0.13
	P6 *	122.	221.	324.	0.12	0.18
	P7	204.	370.	544.	0.10	0.17
01/01/98	P5	25.3	49.6	73.9	0.08	0.21
2.42	P6 *	49.7	96.6	144.	0.10	0.21
	P7 *	82.0	159.	237.	0.10	0.21
	P8 *	122.	236.	352.	0.10	0.22
	P9	171.	330.	492.	0.20	0.29

* NAV SHALL PREDICT N PERIAPSES AHEAD TO SATISFY THE Tp ACCURACY REQUIREMENT (225 S).

NOTES
1. INTERVAL FROM P = 6 HOURS (12/14/97) TO END OF AB MAINPHASE (01/02/98) : 18 DAYS / 115 ORBITS
2. THESE RESULTS DO NOT INCLUDE MANEUVER EXECUTION ERRORS
3. NAV IS USING A 70% DENSITY UNCERTAINTY (2 σ) FOR Tp ACCURACY ESTIMATES (JPL ATMOSPHERIC DENSITY WORKSHOP, 3/22-23/95)
4. THE Tp REQT CAN BE EXCEEDED OCCASIONALLY AT THE EXPENSE OF A SMALL AMOUNT PROPELLANT USAGE FOR ATTITUDE CONTROL : 240. S FOR P = 6 HRS, 260. S FOR P = 3.3 HRS AND 297. S FOR P = 1.9 HRS (REF. 5.3).

5.3.4 ORBITAL ANALYSIS DURING WALKOUT

We have investigated a case during the middle of the 22 day walkout period (first launch). The purpose is to determine the uncertainty associated with the predicted Tp and Rp over a number of periapses after the data acquisition interval. Orbital parameters are given in Table 5.13 and a summary of the data acquisition and analysis strategy is shown in Fig. 5.5 along with Table 5.14. The results are that Nav can predict to P12 (within 225 s).

TABLE 5.13 ORBIT PARAMETERS AND DENSITY MODEL AEROBRAKING WALKOUT PHASE

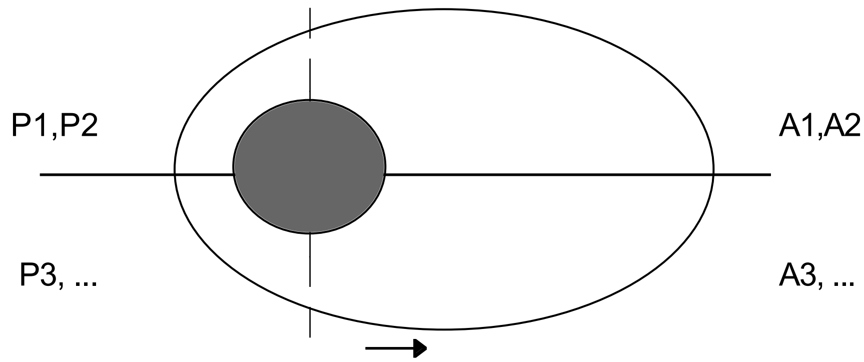
Epoch (ET)	01/10/98 12:40:05	OTHER CONSTANTS Quantity	Value
Tp (P1)	01/10/98 14:11:08		
Period (Hrs)	2.0	Mass (kg)	745.
Altitude (km)	133.93	Cd	1.95
Latitude (deg)	58.8	Area (m^2)	17.04
a (km)	3843.54	$\frac{M}{Cd*A}$	22.42 kg/m^2
e	0.08565		
Ω (deg)	-32.880	Due to atmospheric drag :	
I (deg)	92.713	ΔP (s)	4.79
ω (deg)	58.952	Δa (km)	1.69
TA (deg)	0.0	Δe	0.00039
Rp (km)	3514.357	ΔRa (km)	3.3
Simulation For	Tp Accuracy		

THREE PARAMETER, STATIC, ATMOSPHERIC DENSITY MODEL

ρ_o (x 10^{-06} g/m^3)	5.109
h_o (km)	133.925
H (km)	10.27
70% ρ_o (x 10^{-06} g/m^3)	3.576

Coordinate system: Mars centered, Mars mean equator and IAU vector of epoch

TIME OF PERIAPSIS PASSAGE PREDICTION STRATEGY




```
                         To

                       D/L                      U/L
I--------------I----------------I*I-------------------I-------------I*I----

P    ± 0.5        1.0                  3.0          1.0
                       TIME INTERVAL, HOURS

  NO          NAV DATA        NAV          GRD
 DATA       ACQUISITION    ANALYSIS    PREPARATION
```

PURPOSE : PROVIDE PREDICTED Tp AND Rp FOR SPACECRAFT ENTRY INTO NEXT DRAG PASS (PERIAPSIS)

TIME INTERVALS ARE APPROXIMATE

Fig. 5.5 Graphic representation of tracking data acquisition and orbit determination strategy (orbital period = 2 hours).

TABLE 5.14 PREDICTION ACCURACY FOR TIME OF PERIAPSIS PASSAGE DURING WALKOUT

DOPPLER DATA, ERROR MODELS AND DENSITY RESULTS

DOPPLER DATA
- TWO ORBITS PLUS 1 HOUR PAST P2
- NO DATA WITHIN 0.5 HOUR OF PERIAPSIS
- σ (DOPPLER) = 0.2 MM/S (60 S)

MODELS AND A PRIORI UNCERTAINTIES

MODEL	SOURCE / COMMENT
25 X 25 GMM-1	JGR, 98, 11/25/93
EXPONENTIAL DENSITY (3 PARAMETER)	MARSGRAM V 3.31 (ρ_o = 5.109 kg/km^3)
S/C REM THRUSTING AROUND PERIAPSIS	MAGELLAN OPERATIONS EFFECTIVE 15 MM/S UNCERTAINTY (1σ)
OTHER CONSIDERATIONS	
RESIDUAL ACCELERATION	MO OPERATIONS
SCALE HEIGHT UNCERTAINTY	1-2 KM OR FIX
GM UNCERTAINTY	σ = 0.0512 KM^3 / S^2
BALLISTIC COEFFICIENT	FIXED

ESTIMATE
- STATE, DENSITY, 4X4 GRAVITY FIELD AND PERIAPSIS THRUSTING PERTURBATION (P1, P2)

CONSIDER
- 25 X 25 GRAVITY FIELD, RESIDUAL ACCELERATION , 70% DENSITY VARIATION (P3, P4, ...) AND PERIAPSIS THRUSTING (P3, P4, ...).

RESULTS
- Tp PREDICTIONS FOR PERIAPSES P3 THROUGH P12 ARE WITHIN THE 225. S ACCURACY REQUIREMENT.

DRAG ACCELERATION EFFECTIVE WITHIN PERIAPSIS $\pm$ 15 MIN :

TIME	ACCELERATION (KM / S^2)	DYN P (N / M^2)
P1 - 49 S	1.59 X 10^{-6}	0.036
P1+5 MIN	0.28 X 10^{-6}	0.0063
P1+10 MIN	0.50 X 10^{-9}	0.11 X 10^{-4}

The uncertainty in each Tp and Rp is given in Table 5.15; we draw attention to the Rp uncertainties. These are larger than the previous cases because of the low altitude and the nearly circular orbit. The gravity model is dominating the Rp results; these results are within the 1.5 km requirement until P12 for the larger gravity error model. Note that in addition to the nominal gravity field uncertainties, a case was examined in which these uncertainties were increased by a factor of three. The formal uncertainties were increased because they are usually an optimistic assessment of true or realistic errors and to investigate potentially larger errors.

TABLE 5.15 NAVIGATION RESULTS DURING WALKOUT

EPOCH AND ORBITAL PERIOD (HRS)	PERI- APSIS	PREDICTED UNCERTAINTIES			
		Tp (s) (DENSITY VARIAT)		Rp (km ; 1 σ) (60% DENSITY)	
		60%	90%	GRAVITY	3X GRAVITY
01/10/98	P3	---	---	---	---
2.0	:				
	P8	58.6	87.9	0.16	0.33
	P9	82.3	123.	0.17	0.36
	P10	109.	163.	0.18	0.40
	P11	140.	209.	0.22	0.44
	P12	176.	265.	0.27	0.49
	P13	218.	327.	0.30	0.53

5.3.5 GRAVITY CALIBRATION SIMULATION AND RESULTS

The gravity calibration phase of the mission is very important for navigation. As a result of this data acquisition and analysis, we expect a significant improvement over our baseline gravity field model. The gravity field model used in this plan is the Goddard Mars Model (GMM-1) published in Nov. 1993. (A newer gravity field has been derived at JPL (MARS50C) and will be used in operations. Both the coefficients and one sigma uncertainties for MARS50C are given in Appendix 9.5.)

Previously,the gravity calibration period was expected to occur immediately after the OCM (orbit correction maneuver) propulsive maneuver (i.e. nine days after TMO) which puts the spacecraft in the mapping orbit. However two recent decisions have occurred. The GC shall occur from tracking data acquired between ABX and TMO and the OCM has been replaced by the OTM-1 (i.e. the frozen orbit maneuver). Because of these recent changes, only preliminary results are available for the expected gravity field improvement. However because tracking data are being continuously acquired over this 25 day interval, the gravity field results will be similar to those obtained from the original GC simulation. For the original simulation, seven days of tracking data (two-way coherent doppler) were acquired and a 25th degree and order gravity field was estimated in order to determine the accuracy of the gravity field. These results are compared to the baseline gravity model in Figure 5.6 which gives the ratio σ(GMM1) / σ(GC) for each coefficient of a 25 x 25 field resulting from the gravity calibration simulation. This figure shows a) the low-order coefficients are improved by a factor of 3 to 10, b) the middle-order terms are improved basically by a factor of 10 to 20 and c) the high-order terms are improved by a factor of 3 to 10. In the last grouping, some individual coefficients are improved dramatically; these are the high order terms of a particular degree. The net result of the gravity calibration analysis is that we should expect a strong improvement in spacecraft position accuracy during flight operations once the gravity model has been developed. To demonstrate this, we compare the reconstructed position accuracy of the spacecraft using the baseline gravity model (GMM-1) and the GC-derived gravity model in Table 5.16. As shown all position component accuracies improve by a factor of ten or more.

Fig. 5.6 Gravity model improvement : GMM-1 vs. GC

TABLE 5.16 COMPARISON OF RECONSTRUCTED POSITION ACCURACY -- GMM-1 GRAVITY FIELD VERSUS GRAVITY CALIBRATION FIELD

	Reconstructed Position Accuracy At Periapsis (km, 1σ)			
Epoch	Downtrack	Crosstrack	Radial	Comment
3/11/98	2.23	3.62	0.049	GMM-1 Gravity Field
3/11/98	0.14	0.23	0.005	GC Derived Field

These GC results are representative of position accuracy improvement for the beginning of mapping.

5.4 MAPPING PHASE

Mapping begins in mid-March,1998 and extends 687 days to 1/31/2000. The purpose of this section is to evaluate the spacecraft's position uncertainty for selected dates throughout this phase.

5.4.1 ORBITAL KNOWLEDGE AND PREDICTION

The nominal plan during mapping is to acquire doppler data during one tracking pass (10 hours duration) per day. During selected intervals, that is when the MGS orbit is edge-on as seen from earth, DSN coverage will increase to two passes per day. The duration of this coverage will be 28 days centered on these two dates 10/29/98 and 2/19/99.

Other tracking data may become available for navigation purposes. This primarily includes an additional tracking pass approximately every third day for the acquisition of real-time science data. However, these passes may be downlink-only thus only one-way doppler shall be acquired. When referenced to the USO as the frequency source, the MO experience was that these data were very precise but exhibited a significant linear bias.

In this context, spacecraft orbital knowledge or reconstructed accuracy applies during the interval that tracking or navigation data are acquired and analyzed. Past that nominal 10 hour interval, spacecraft orbital accuracy is referred to as predicted.

5.4.1.1 INITIAL MAPPING PHASE

The epoch 3/11/98 marks the beginning of the mapping phase.

Representative uncertainties for the spacecraft's position for both reconstruction and prediction are given in Table 5.17.

TABLE 5.17 SPACECRAFT POSITION UNCERTAINTY AT PERIAPSIS IN THE MAPPING ORBIT

Epoch;	Position Components (km, 1σ)		
Days Past Epoch	Downtrack	Crosstrack	Radial
3/11/98	0.14	0.23	0.005
1	0.19	0.23	0.007
3	0.79	0.24	0.013
7	4.2	0.26	0.067
14	20.5*	--	--

*Approximation based on an analytical formula and a 90% confidence a prior density (1.28 sigma). The ballistic coefficient used was 22.5 kg/m^2.

5.4.1.2 SOLAR CONJUNCTION (5/13/98)

When the spacecraft is within a sun-earth-spacecraft angle of three degrees (from 5/1/98 to 5/30/98), navigation shall be on a best efforts basis. This is because the doppler data shall be degraded and become completely unusable as the raypath passes closest to the sun.

5.4.1.3 EDGE-ON ORBITAL CONFIGURATION (10/29/98 AND 2/19/99)

To compensate for the loss of OD information due to this unique orbital configuration, we have requested an additional daily tracking pass for 28 days centered on the above epochs. In addition, we have requested at least a 3 hour overlap between these two DSN passes in order to acquire differenced doppler data (i.e. the simultaneous acquisition of two-way coherent and three-way doppler). Orbit accuracy results are given in Table 5.18.

Note that the differenced-doppler data are effective in reducing the uncertainty of the cross-track (CT) component of position. Without this data type, the CT position component uncertainty would be 5.2 km (1σ).

TABLE 5.18 RECONSTRUCTED AND PREDICTED SPACECRAFT POSITION UNCERTAINTY AT PERIAPSIS DURING THE EDGE ON CONFIGURATION

Epoch; Days Past Epoch	Position Uncertainty (km ; 1σ) Downtrack	Crosstrack	Radial	Comment
10/28/98	0.020	0.41	0.003	Edge-On (90 deg) ;
2	0.19	0.41	0.006	Differenced Doppler
4	0.41	0.42	0.012	Required
7	0.89	0.44	0.034	
14	3.0 *	---	---	

* Analytical approximation

We expect very similar results to these for the second edge-on configuration. However, the time-interval is shorter as shown in Fig.3.9 and noted as follows: 2/19/99 (90 deg), 2/23/99 (89 deg) and 2/27/99 (88 deg).

5.4.1.4 MARS PERIHELION (11/25/99)

The reason for studying this segment of the mapping mission is the significant increase in Mars atmospheric density as shown in Appendix 9.9. These larger densities are primarily due to the Mars perihelion event and the solar cycle reaching near its maximum. The previous solar cycle maximum occurred during February, 1990.

Throughout this time, navigation shall be estimating atmospheric density parameters on a daily basis. This will be based upon the daily doppler tracking pass and the expected strong a priori gravity model deduced from previous MGS data analysis. Representative spacecraft position accuracies are given in Table 5.19.

TABLE 5.19 RECONSTRUCTED AND PREDICTED SPACECRAFT POSITION UNCERTAINTY AT PERIAPSIS DURING PERIHELION (11/25/99)

Epoch;	Position Uncertainty (km, 1 σ)			
Days Past Epoch	Downtrack	Crosstrack	Radial	Comment
11/25/99	0.59	0.23	0.006	Estimate density
1	0.68	0.23	0.01	
3	4.1	0.23	0.03	
7	24.2	0.24	0.10	
14	97.*	--	--	

*Approximation based on analytical formulae and a ballistic coefficient of 22.5 kg/m^2. This is a conservative prediction accuracy because it does not account for atmospheric density information gained previously from navigation flight operations. The improved or more accurate atmospheric density estimates are expected to come from a) the aerobraking phase and b) from tracking data acquired and analyzed during this and the previous Mars perihelion.

5.5 RELAY PHASE

This phase covers a six month period from 1/31/2000 to 7/31/2000 in which the MGS spacecraft shall act as a relay for landed stations and/or rovers. Navigation OD results shall be addressed at a later date.

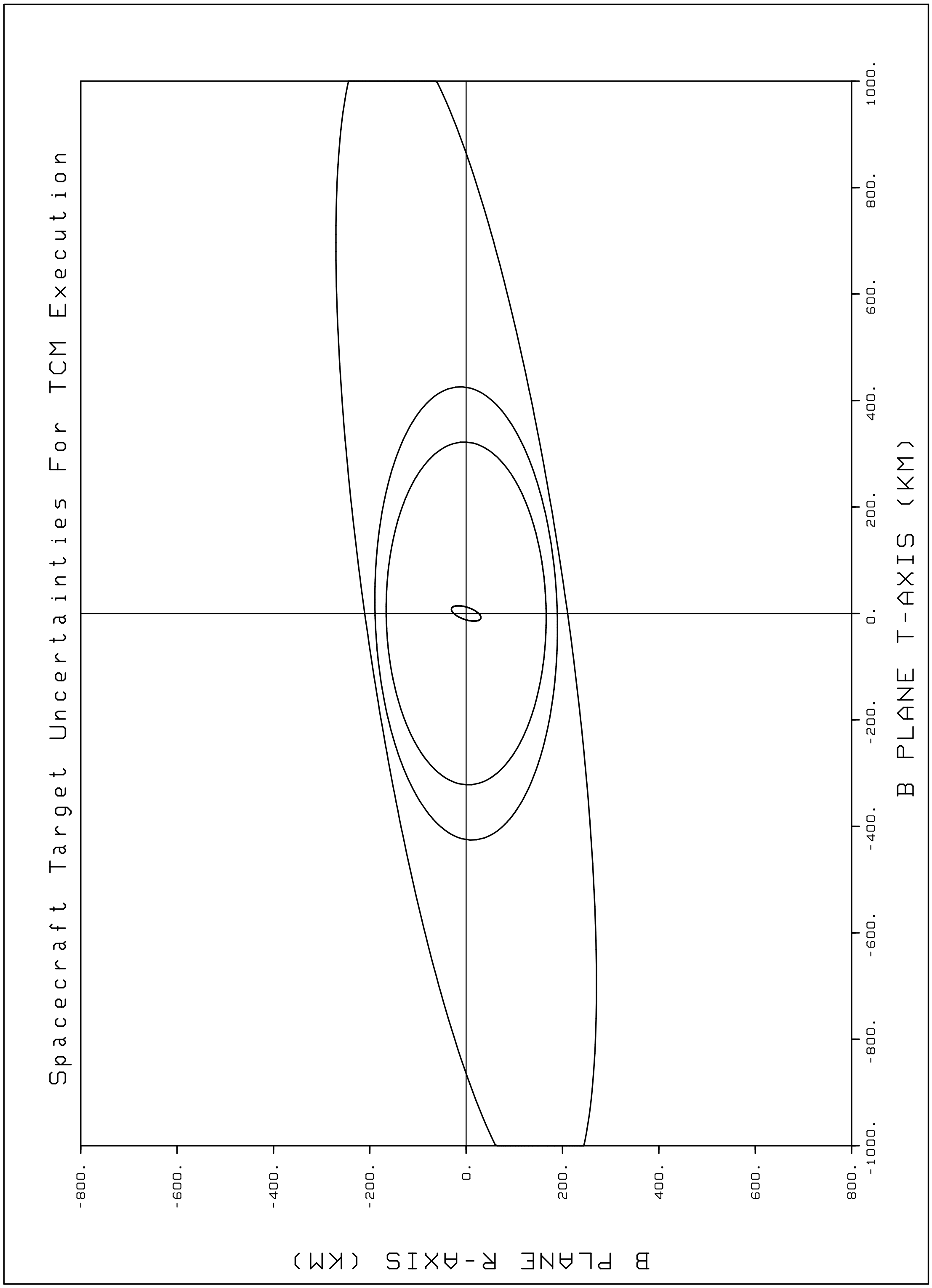


Fig. 5.1 Spacecraft Target Uncertainties For TCM Execution
11/06/96 Launch

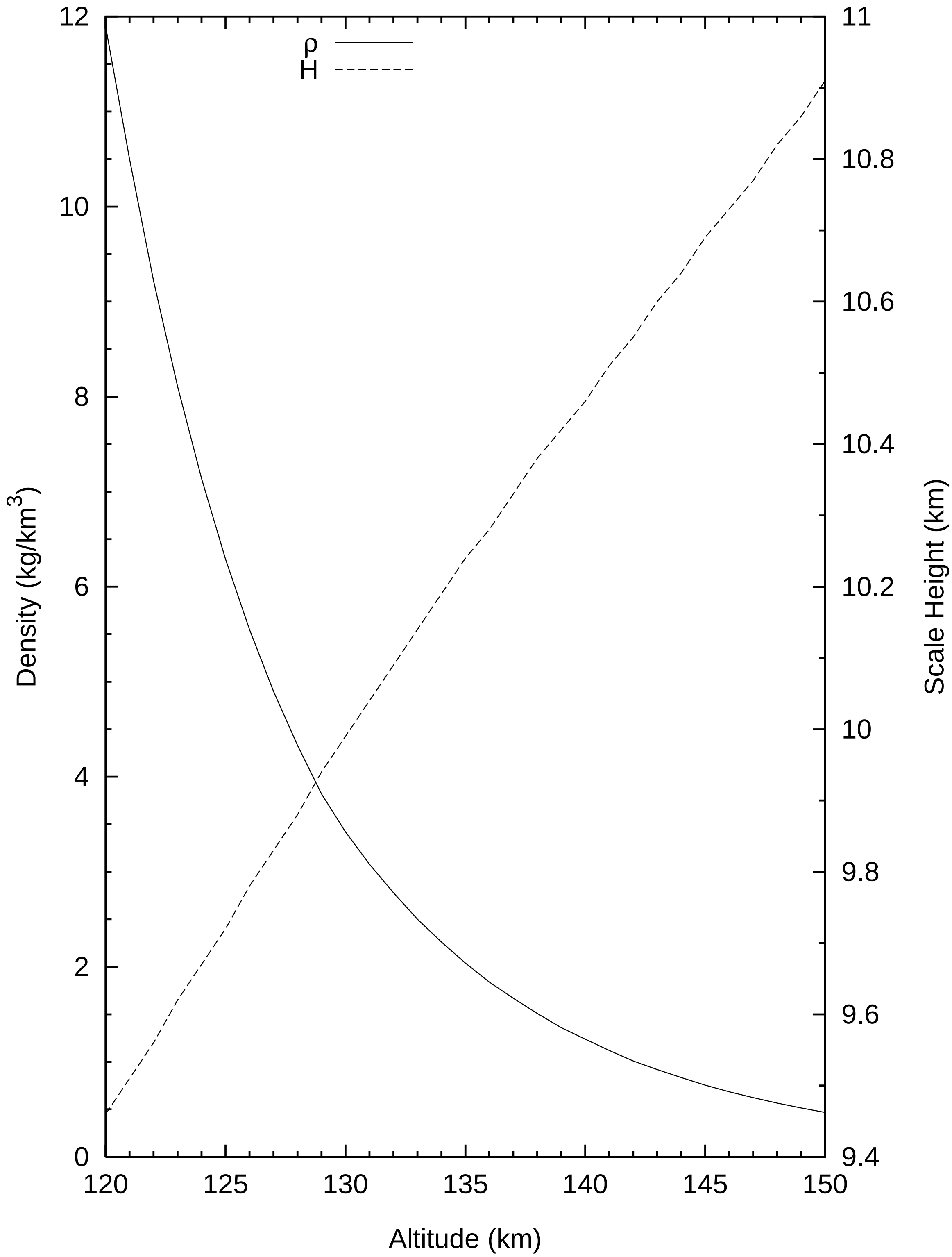


Fig. 5.3 Nominal Atmospheric Density As A Function of Altitude

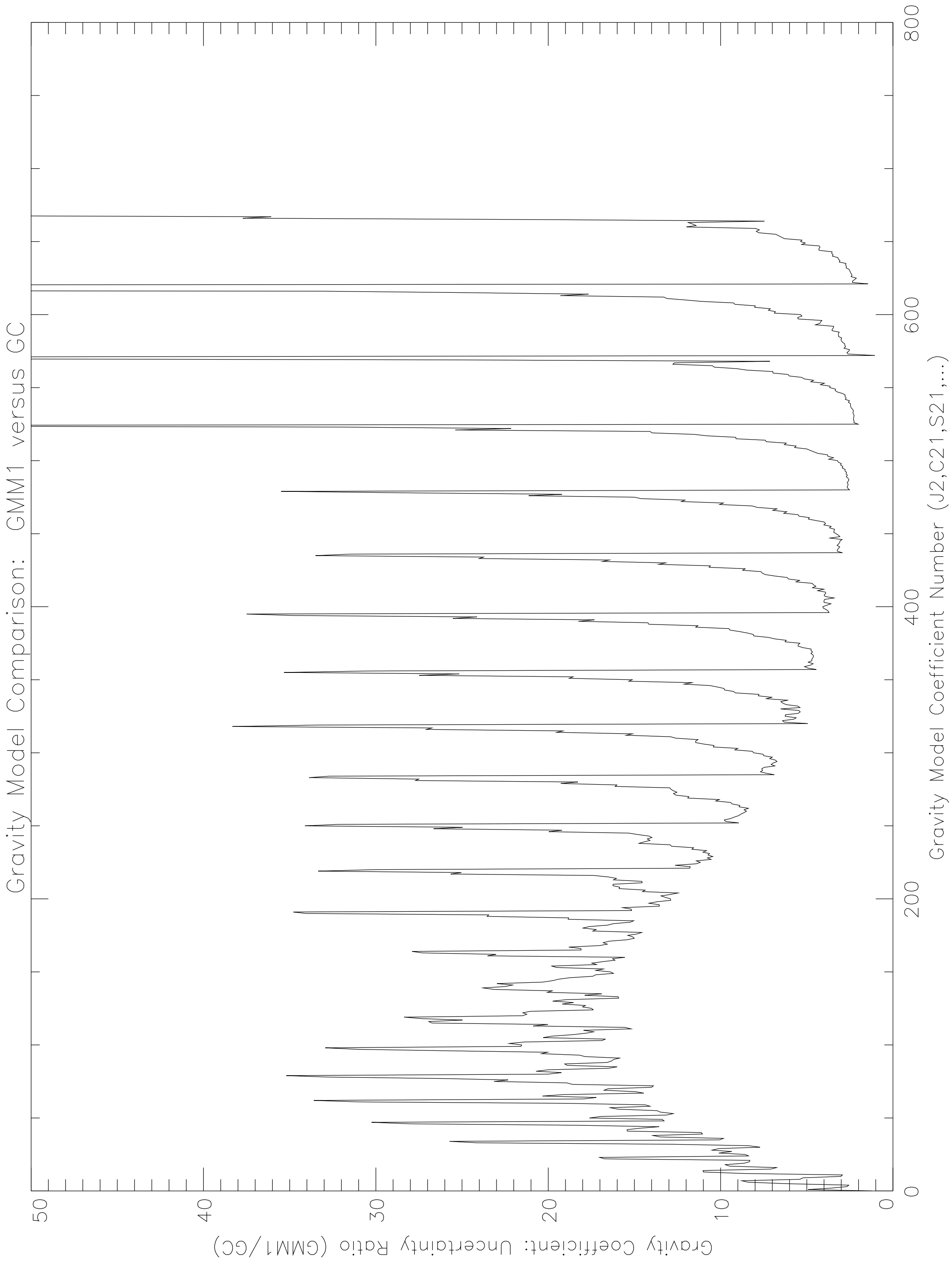


Fig 5.6 Mars Gravity Model Improvement: GMM1 vs GC

6. PROPULSIVE MANEUVER ANALYSIS

6.1 INTRODUCTION

During each phase of the Mars Global Surveyor Mission, it will be necessary to execute several maneuvers to ensure that the spacecraft is in the desired trajectory. At each maneuver, the spacecraft velocity is changed appropriately, to provide the necessary trajectory correction.

In the interplanetary or cruise phase, the injection errors must be corrected soon after launch so that the spacecraft is on its desired course towards Mars. This trajectory correction maneuver (TCM) must be followed by other maneuvers to compensate for orbit determination (OD) errors at the time of maneuver as well as for execution errors in the maneuver itself. The sequence of TCMs is terminated with a maneuver about three weeks prior to Mars Orbit Insertion (MOI) so that at encounter, the spacecraft is precisely delivered for propulsive capture in the nominally desired orbit about Mars. The launch period for the MGS mission extends from November 5, 1996 to November 25, 1996. Details on the reference trajectories for various launch dates are available in Refs. 6.1 and 6.2. The interplanetary maneuver analysis will focus on the trajectories for the November 6th and November 24th launch dates. The earlier launch date is the more favorable of the two, in terms of interplanetary cruise Δv requirements. Between injection in November 1996 and Mars encounter in September 1997, 4 trajectory correction maneuvers (TCMs) will be executed to ensure that the spacecraft state at encounter is acceptable to proceed with Mars Orbit Insertion maneuver.

The Orbit Insertion phase or the second phase of the MGS mission, extends from Mars encounter, through the preliminary (and intermediate) capture/drift orbits, until the spacecraft is in a near-circular, ‘frozen’, near-polar, Sun synchronous orbit, and declared ready for the Mapping phase. The OI phase extends from September 1997, through possibly the middle of March 1998. The initial capture orbit will be an eccentric orbit with a period of about 48 hours and a periapsis radius of 3700 km. The insertion maneuver for 48-hour capture orbit requires a Δv expenditure in the range of 950 to 1000 m/sec (Ref. 6.1).

The near-circular ($e \cong 0.007$) mapping orbit is of radius 3775.2 km, with an inclination of 92.87° and an argument of periapsis of –90°. The transition from the capture orbit to the mapping orbit will be accomplished by aerobraking with propulsive assists. Actually, “gravity calibration” will be carried out during the last part of the second or “orbit insertion” phase of the mission.

The mapping phase of the mission will last for about 2 years, from March 1998, depending on the actual launch date. After the mapping phase, the spacecraft will be raised to the quarantine orbit, where it will remain for the approximately 3-year relay mission phase. Orbit trim-maneuvers (OTM) will be necessary to maintain the orbital elements within acceptable limits about the ‘frozen orbit’.

A major consideration in maneuver analysis for the MGS mission is to ensure that the NASA planetary protection requirements are satisfied throughout the mission. *Details on the quarantine requirements and their impact on maneuver analyses for the interplanetary phase will be discussed in the sections to follow*. Satisfying the quarantine conditions during the entire MGS mission, especially over the extended period of 50 years since launch, will be discussed later.

6.1.1 APPROACH TO MANEUVER ANALYSIS AND DESIGN

The purpose of maneuver analysis is to determine the time of execution of each maneuver during the mission and the velocity change (vector Δv) to be imparted to the spacecraft at each maneuver. With strategies for optimization whenever applicable, the total fuel consumption (total Δv) must be minimized, while satisfying all the mission constraints and requirements. Issues relating to only propulsive maneuvers are discussed here. At each maneuver, random errors in the knowledge of the spacecraft state (OD errors) at the time of maneuver and random errors in executing the maneuver, will affect the desired (nominally calculated) and actually implemented values of the change in the spacecraft velocity and hence its subsequent trajectory. Corrections have to be obviously made at the next maneuver as necessary. In pre-flight analysis, the total propellant (Δv) to be carried on-board the spacecraft is determined to 95% and 99% confidence levels.

The Monte Carlo simulation process is a natural choice for maneuver analysis just as in previous missions. Starting with the spacecraft in its nominal initial state, the desired phase of the mission is “flown” in simulation, sampling from injection errors, orbit determination errors and execution errors as appropriate at each maneuver, to provide perturbations to the spacecraft trajectory. Salient results such as delivery aim-points and Δv at each maneuver from all the “sample flights” are retained. From a statistical number of simulated flights (actually 5000 in each case in the present analysis) the mean values and standard deviations for all the pertinent quantities (including propellant requirements) are calculated.

The Monte Carlo algorithm for the interplanetary phase maneuver analysis can be described as follows:

A. Perturb the nominal spacecraft trajectory at injection by sampling the Delta 7925 Third Stage injection error distribution and determine the resulting delivery error at Mars.

B. Interplanetary Maneuvers:

   1. Propagate the spacecraft state from the previous maneuver to the current maneuver time.
   2. Perturb the nominal spacecraft state by the OD error distribution to determine the “observed” spacecraft state to compute Δv.
   3. Determine the nominal maneuver Δv which will correct the errors resulting from the previous maneuver, redirecting the spacecraft to the appropriate aim-point.
   4. Perturb the nominal computed maneuver by sampling the execution error distribution, simulating the actually implemented Δv correction at this maneuver.
   5. Determine the delivery error at Mars due to the OD and maneuver execution errors.

C. Repeat this process until all the maneuvers have been modeled and the various statistical parameters such as the mean and standard deviation for the delivery aim-points and the Δv’s have ‘converged’.

The brief description above is provided just to facilitate understanding the statistical results in this chapter.

The Monte Carlo simulations for the OI and Mapping phases of the MGS mission follow the same outlines.

6.1.1.1 ORBIT DETERMINATION ERRORS

At each maneuver, the spacecraft velocity is changed depending on the difference between the desired (exit) state of the spacecraft just after the maneuver and the ‘observed’ (incoming) spacecraft state just before the maneuver. Hence errors in orbit determination (OD errors) are critical for the accuracy of maneuver analysis. *OD error estimates as appropriate at the various trajectory correction maneuvers are presented in Tables 5.2 and 5.3 of this report*.

6.1.2 PROPULSION SYSTEM

A brief description of the propulsion system for the Mars Global Surveyor Mission is available from the document on “Spacecraft Development, Integration and Support” from Martin Marietta Astronautics (Ref. 6.3). Accordingly, the main engine will be the Royal Ordnance LEROS-1b dual-mode, bipropellant system using NTO and hydrazine. Additionally, four rocket engine modules (RTMs) are provided, each with two aft-facing thrusters and one roll control thruster.

6.1.2.1 THRUSTER PERFORMANCE AND CHARACTERISTICS

From Ref. 6.3, it is understood that the main engine (LEROS-1b) can deliver a nominal specific impulse (I_{sp}) of 318 seconds, with a minimum rating of 317 seconds. It has a nominal thrust rating of 596 ± 9 N.

The specific impulse and the uncertainty in its nominal value are taken into account during the Monte Carlo analysis of maneuvers leading to the Orbit Insertion phase. These values do not enter the computations for Δv directly. However, the spacecraft mass is corrected consistent with these values, before and after the Orbit Insertion maneuver, to obtain more reliable estimates of Δv.

As already mentioned, the propulsion system consists of 4 rocket engine modules (REMs) besides the main engine. Each REM consists of three 4.5 N (1 lb-f) thrusters (Rocket Research MR-111C). Two thrusters in each of the four modules are aft-facing and the third is for roll control. The eight aft-facing thrusters are arranged in two redundant strings with provision for isolation of a string in case of a thruster failure due to malfunction in the thruster valve or latch valve.

It may be of interest to note for comparison that the MO mission had 4 main engines rated at 490 N, 4 engines rated at 22 N, 8 engines rated at 4.4 N and 4 engines rated at 0.9 N. The nominal specific impulse values of these engines were 311, 272.5, 148 and 120 seconds respectively.

6.1.2.2 ENGINE SYSTEMS AND INTENDED UTILIZATION

The first trajectory correction maneuver (TCM-1) scheduled 15 days after injection and the Mars Orbit Insertion (MOI) maneuver will be executed with main engine burns.

Several options have been examined in detail for TCM-2, the second trajectory correction maneuver; a straight-forward 2-impulse optimization in conjunction with TCM-1, a ‘K-inverse’ strategy to simply follow TCM-1 (implemented under a K-inv. strategy also) and finally, a '**blowdown biprop**' maneuver limited to a maximum Δv of 6 m/s. In the third option of the blowdown maneuver also, TCM-1 and TCM-2 are designed together under the 2-impulse optimization strategy. From Ref. 6.4, it may be noted that the blowdown TCM-2 maneuver allows the "high pressure latch valve to be closed" or to "pyro-isolate the pressurant after TCM-1 until MOI", providing an additional margin of safety for the spacecraft systems integrity. Consequently, the 'blowdown TCM-2' maneuver is the baseline and hence it is emphasized throughout the discussion here on interplanetary phase maneuver analysis.

The trajectory correction maneuvers TCM-3 and TCM-4 and the orbit maintenance maneuvers during the mapping phase will be carried out firing the small thrusters (on the REMs), which will also be used for attitude control. The thrusters will also be used for vehicle control during main engine burns.

6.1.2.3 MANEUVER EXECUTION ERRORS

The accuracy with which a desired maneuver can be implemented is limited by the spacecraft engine hardware and the guidance system performance. Errors in implementing a maneuver can be characterized as dependent on the magnitude of the maneuver and on the errors in pointing the thrust vector. Errors in each category (magnitude errors and pointing errors) are considered to be comprised of a fixed part and a part proportional to the maneuver magnitude as shown in Table 6.1. The analyses and results presented here are based on the error values listed in Table 6.1. It must be emphasized that these are the "MGS mission specification(s)" for maneuver execution errors.

The achievable accuracies of maneuver execution or the "capability errors" for the MGS mission have been outlined in a recent memo (Ref. 6.5) dated May 23, 1995, from Eileen Dukes of Lockheed-Martin. From Ref. 6.5, it is seen that the proportional magnitude error may actually be less than 0.2% (just about one-tenth the specification) and the "fixed side velocity" essentially zero for main engine burns. This is particularly of interest for TCM-1 and OI maneuvers. Similarly, the proportional magnitude and pointing errors for the hydrazine thrusters are likely to be about one-third of the "MGS specification" values, while the fixed magnitude and pointing errors (for hydrazine burns) are essentially insignificant compared to specification. However, since the confidence levels for the error values published in Ref. 6.5 are not explicitly given, the entire analysis discussed here will be based only on the MGS specifications for maneuver execution errors as in Table 6.1.

TABLE 6.1. MANEUVER EXECUTION ERRORS.

(Specified 3-Sigma Execution Errors for all Maneuvers.)

Error Source		Error
Fixed Magnitude		0.05 m/sec
Proportional Magnitude		2.00%
Fixed Side Velocity	Total Per Axis	0.01 m/sec 0.00707 m/sec
Proportional Side Velocity	Total Per Axis	2.5% 1.768%

6.1.2.4 PRE-CALIBRATION MANEUVER EXECUTION ERRORS

Although it is quite desirable for a calibration maneuver to be performed on each of the engine systems to determine its error characteristics before first use, such calibration is not likely, especially before TCM-1, the first trajectory correction maneuver.

However, the LEROS-1b main engine would have been evaluated following TCM-1; so also the small thrusters on the rocket engine modules (REMs) following the various attitude control burns and in any case, following TCM-3 and TCM-4. Hence the propulsion system would have been completely evaluated (or calibrated) before the Mars Orbit Insertion maneuver.

Pre-calibration Maneuver Execution Errors for the MGS mission will be discussed at a later date, if necessary.

If it is required to relax the maneuver execution errors from the values listed in Table 6.1, a waiver would be necessary and it would be submitted by the contractor.

6.2 INTERPLANETARY PROPULSIVE MANEUVER ANALYSIS

6.2.1 INTRODUCTION

The interplanetary phase maneuver analysis for the Mars Global Surveyor mission will be presented in this report, focusing on the trajectories for launch dates 11/06/96 and 11/24/96. It is considered that these two cases are quite representative of the disparity in the injection errors associated with the different interplanetary trajectories for the MGS mission, during the launch period in 1996.

The essential task is to determine the time of maneuver and Δv for each trajectory correction maneuver, TCM-1 through TCM-4, and select the aim-points for each maneuver to satisfy “Planetary Protection Requirements”, while minimizing the total Δv for the interplanetary phase of the mission. Operational logistics also play a major role in scheduling the maneuvers.

Furthermore, all the TCMs (for both trajectories with launch dates on 11/06/96 and 11/24/96) are designed *satisfying the sun-angle constraint* that at each maneuver, the Δv vector makes an angle $\geq 30°$, with the spacecraft-sun vector; it may be recalled that in the “Preliminary Navigation Plan” (Ref. 6.7) for the MGS mission, the sun-angle constraint condition had not yet been considered. By appropriate choice of maneuver date(s) and aim-point(s), any violation of the sun-angle constraint is simply avoided in the navigation plan.

Before proceeding to the details, it will be useful to understand the scope of the work, so that the results presented finally in the navigation plan can be fully appreciated. For each launch date, as many as 30 aim-points on the “10^{-5} allowable planetary impact probability (at launch) contour” were examined in detail for maneuver analysis. The maneuver date for TCM-2 was also parametrically varied from 21 days to 120 days after TCM-1, at about 5-day intervals. Trajectory correction maneuvers based simply on the K-inverse strategy or on 2-impulse optimization of TCMs 1 and 2 were investigated in each case (defined by the biased launch aim-point and maneuver date for TCM-2). Particularly, the 2-impulse optimization strategy was re-examined in each case, with **TCM-2 as a blowdown maneuver limited to a maximum Δv of 6 m/sec**. It has been ensured that the planetary quarantine conditions and sun-angle constraints are satisfied for all the recommendations made and results presented.

6.2.2 PLANETARY PROTECTION REQUIREMENTS

The preliminary recommendations (submitted for review) to the NASA Planetary Protection Officer for the Mars Global Surveyor mission have been outlined in a memo dated June 9, 1994, from Barengoltz (Ref. 6.8). An updated plan will be shortly made available (Ref. 6.9).

Accordingly, the probability of impact on Mars by the launch vehicle and hence the spacecraft, must be less than 10^{-5} at launch. Biasing the aim-point at launch helps to satisfy this condition.

Furthermore, for the present analysis, it is considered that the probability of impact on Mars by the spacecraft is not to exceed 10^{-2} at each trajectory correction maneuver during the interplanetary phase. Together with the assumption that the probability of failure of the “next maneuver” is 10^{-2}, this implies that the probability of impact on Mars by the spacecraft is $< 10^{-4}$ at each maneuver (during the cruise phase). The cumulative probability of the MGS spacecraft impacting on Mars is approximately 1.79×10^{-4} and 2.23×10^{-4} respectively for the launch dates of 11/06/96 and 11/24/96 as seen in Table 6.6 and Table 6.7. Besides at launch, the delivery aim-points are biased at TCM-2 and at TCM-3, to satisfy the planetary protection condition. The 2-impulse optimization algorithm selects the aim-point for TCM-1 sufficiently far from the final aim-point, that planetary quarantine is automatically satisfied. By TCM-4, the delivery dispersion is so small that the impact probability is negligible.

Whenever necessary, (at launch and TCMs 1-3), the aim-points are selected, biased with respect to the nominal final delivery aim-point at encounter, by an iterative process. With trial values for the aim-points at launch and at each TCM (1 through 4), a Monte Carlo run (with 5000 samples) is carried out to determine the mean delivery aim-points and dispersions, sampling from error distributions due to injection, OD and maneuver execution errors. With the mean delivery aim-point and dispersions at each step (at launch or at any TCM) from the Monte Carlo run, the probability of impact on Mars and if necessary, newer values of biased aim-points satisfying planetary quarantine conditions at that step, are obtained from the two links PQ and PQPLOT of the MOPS library (Ref. 6.10). With the new values for aim-points and constraints as necessary, the Monte Carlo analysis is rerun and the process is repeated till planetary protection requirements are satisfied during the entire interplanetary phase. The results in Tables 6.6 and 6.7 are obtained from such an iterative analysis.

The long-term requirements on the probability of impact on Mars by the spacecraft will not be addressed here.

6.2.3 LINEARIZED MANEUVER ANALYSIS - A MATHEMATICAL MODEL

The actual trajectories incorporating the 4 TCMs and biased aim-points (at launch and at the first three correction maneuvers), obviously do not coincide with the nominal reference trajectory. However, the trajectory for each sample case in the Monte Carlo run is not obtained by numerical integration. The analysis is by the theory of linear perturbations for 'sufficiently small deviations'.

The partial derivatives of the spacecraft state at the time of encounter in the Mars B-plane coordinate system with respect to the instantaneous cartesian spacecraft state (at the integration time) are computed along with the nominal spacecraft trajectory for linear perturbation analysis. The matrices of these partial derivatives, known as **K**-matrices, are stored at specific time intervals - of 1 day in the present case - from injection to encounter. In maneuver analysis, it is desired to control the two components (**B•R**) and (**B•T**) of the miss-vector (**B**) in the B-plane as well as the 'linearized time of flight' - (LTF), which, together, constitute a 3-component vector of controlled or dependent variables. The three components of the spacecraft velocity, which can be modified by firing the thrusters, constitute the control variables.

The analysis is expressed in mathematical terms by the following equations:

$$\Delta\mathbf{B}=\mathbf{K}\Delta\mathbf{v} \tag{6.1}$$

where $\Delta\mathbf{B}$ is desired change in the vector {(**B•R**), (**B•T**), LTF}, and $\Delta\mathbf{v}$ is the required change in the spacecraft velocity and **K** is the matrix of partials explicitly given by

$$\mathbf{K}=\begin{bmatrix} \frac{\partial(\mathbf{B}\bullet\mathbf{R})}{\partial\dot{x}} & \frac{\partial(\mathbf{B}\bullet\mathbf{R})}{\partial\dot{y}} & \frac{\partial(\mathbf{B}\bullet\mathbf{R})}{\partial\dot{z}} \\ \frac{\partial(\mathbf{B}\bullet\mathbf{T})}{\partial\dot{x}} & \frac{\partial(\mathbf{B}\bullet\mathbf{T})}{\partial\dot{y}} & \frac{\partial(\mathbf{B}\bullet\mathbf{T})}{\partial\dot{z}} \\ \frac{\partial(\mathrm{LTF})}{\partial\dot{x}} & \frac{\partial(\mathrm{LTF})}{\partial\dot{y}} & \frac{\partial(\mathrm{LTF})}{\partial\dot{z}} \end{bmatrix} \tag{6.2}$$

In particular, when the matrix **K** is non-singular, the change in velocity, $\Delta\mathbf{v}$, necessary to obtain the desired correction $\Delta\mathbf{B}$, is given by

$$\Delta\mathbf{v} = \mathbf{K}^{-1}\,\Delta\mathbf{B} \tag{6.3}$$

The following observations must be emphasized concerning equations (6.1-3). The spacecraft state is obviously 6-dimensional in any coordinate system. However, since only the three components of the spacecraft instantaneous velocity can be modified in flight, the control or maneuver problem in equations (6.1-3) is simply a 3-dimensional representation obtained by appropriately partitioning the full 6-dimensional case. Secondly the terms in the first two rows of the **K** matrix are the partial derivatives of (**B•R**) and (**B•T**) at Mars encounter with respect to the current spacecraft velocity. Finally, the terms of the **K** matrix at any particular time indicate as to how effectively a maneuver at that time can correct targeting errors as seen from Eq. (6.3).

6.2.4 DELTA THIRD STAGE INJECTION ERRORS

Orbit determination and maneuver execution errors, which are relevant to all phases of the mission, have already been discussed. Since injection errors are more pertinent to the interplanetary phase of the mission, they are discussed now.

The injection error covariance matrices of the Delta 7925 rocket's third stage are available from a series of communications (Refs. 6.11, 6.12, 6.13 and 6.14) from McDonnell Douglas Aerospace; in particular, the error covariance matrices are presented for the trajectories corresponding to the launch dates of 11/06/96 and 11/16/96. Actually, Ref. 6.14, is the authoritative document comprising of the results in Refs. 6.11, 6.12 and 6.13.

In Ref. 6.11, the covariance matrices are given (for 11/06/96 and 11/16/96 launch) for a third stage nominal spin rate of 70 RPM, pertaining to nutation time constants of 30, 40, 60 and 80 seconds. Moreover, the "velocity deficit probabilities" and the "sensitivities of the orbit insertion (TECO) state parameters to a second stage velocity deficit" are also presented for the launch on 11/06/96 only, with a 98.89% probability of no velocity deficit.

In Ref. 6.12, the distribution function for the velocity deficit due to second stage propellant depletion for the case of 95% Probability of Command Shut-down (PCS) is given without any specific reference to sensitivities.

In Ref. 6.13, the injection covariance matrices corresponding to a nominal Delta third-stage spin rate of 59.01 RPM and nutation time constant of 30 seconds are presented for the November 6th and 16th launch dates in 1996.

The entire discussion here on interplanetary phase maneuver analysis for the 11/06/96 launch date, will be restricted to the injection errors (and launch velocity deficiencies) presented in Refs. 6.11 and 6.12 only, except where it is explicitly stated to be otherwise, such as for the results in Tables 6.8 through 6.12, with entries corresponding to a nominal spin rate of 59 RPM and nutation time constant of 86 seconds. Moreover from numerous analyses, it has been determined that the injection covariance matrices corresponding to a nutation time constant of 30 seconds lead to slightly higher or more conservative Δv estimates; hence results corresponding to these cases have been discussed in Tables 6.2 through 6.7, almost exclusively.

Injection error covariance matrices for the launch on 11/24/96 are not yet available from McDonnell Douglas. However, since from preliminary work it is felt that the trajectory corresponding to 11/24/96 will present more challenging conditions, **the covariance matrix for 11/16/96 launch date** is used for analysis of the launch date on 11/24/96 for the MGS mission. Furthermore, wherever necessary for analysis, the velocity deficiencies due to PCS and injection state sensitivities to such velocity deficits are taken from the corresponding tables for the 11/06/96 launch date, from Refs. 6.11 through 6.13. In short, corresponding to 11/24/96 launch, the analysis is based on the K-matrices for the trajectory of 11/24/96, the injection error covariance matrices corresponding to 11/16/96 and velocity deficiencies and injection state sensitivities pertaining to 11/06/96.

The penalty of injection errors is conveniently assessed from the $\Delta \mathbf{v}$ required at TCM-1 to redirect the spacecraft to the desired aim-point at encounter. The 'figure of merit' (**FOM**) is **a measure of the $\Delta \mathbf{v}$** required at TCM-1 to compensate for injection errors, *in the absence of* OD *and maneuver execution errors as well as planetary protection requirements*. The figure of merit is calculated from the following equations:

$$\overline{\mathbf{P}}_{\mathbf{enc}} = \overline{\mathbf{K}}_{\mathbf{inj}} \overline{\mathbf{P}}_{\mathbf{inj}} \overline{\mathbf{K}}_{\mathbf{inj}}^{\mathbf{T}} \quad (6.4)$$

$$\mathbf{C}_{\mathbf{V}}^{\mathbf{TCM\text{-}1}} = \mathbf{K}_{\mathbf{TCM-1}}^{-1} \mathbf{P}_{\mathbf{enc}} \mathbf{K}_{\mathbf{TCM-1}}^{-\mathbf{T}} \quad (6.5)$$

$$\mathbf{FOM} = \sqrt{\mathbf{Trace}\left\{\mathbf{C}_{\mathbf{V}}^{\mathbf{TCM\text{-}1}}\right\}} \quad (6.6)$$

In the above equations, $\mathbf{P}$ is the 3x3 upper left sub-matrix of the full 6x6 dimensional error covariance matrix $\overline{\mathbf{P}}$ (indicated with an overbar) and $\mathbf{C}_{\mathbf{V}}^{\mathbf{TCM\text{-}1}}$ is the 3x3 covariance matrix of the velocity required at TCM-1 with the superscripts and subscripts being essentially self-explanatory. Equation (6.4) represents mapping injection errors to the time of encounter at Mars; equation (6.5) is the covariance form of Eq. (6.3) - $\{\Delta \mathbf{v}\, \Delta \mathbf{v}^{\mathbf{T}}\}$ at TCM-1.

The FOM for the Delta 7925 Third Stage injection errors is **21.93** m/sec for the MGS mission with launch date 11/06/96 and TCM-1 on 11/21/96 (Launch + 15 days). The FOM for launch on 11/24/96 is **25.33** m/sec with TCM-1 scheduled on 12/09/96, which is also 15 days after launch. These results are derived from the covariance matrices as appropriate for the launch date and corresponding to a third-stage nominal spin rate of 70 RPM and a nutation time constant of 30 seconds. The 95th and 99th percentile total Δ**v** for interplanetary cruise for these two cases are also presented in Table 6.2 for comparison, ranging in values from 42.73 to 65.75 m/s. The conditions for maneuver analysis for these two cases will be discussed in detail in the section on results. The calculated figure of merit (FOM) for the Mars Observer mission (Ref. 6.6) was 28 m/sec for launch on 09/22/92, and 35 m/sec for launch on 10/09/92, with TCM-1 scheduled 10 days after launch. Additional results for evaluation are provided in Tables 6.3 and 6.4 for the MGS mission.

It must be reiterated that the values in Tables 6.2 and 6.4 for MGS launch on 11/24/96 are obtained from injection error covariance matrices pertaining to the launch date of 11/16/96 for a preliminary estimate of the interplanetary Δv's. When the actual injection covariance matrix for 11/24/96 becomes available and when the final covariance matrices are issued for all launch dates, updates to all the results published in this report will be presented as necessary.

6.2.5 SCHEDULING AND OPTIMIZATION OF INTERPLANETARY MANEUVERS

TCM-1 and TCM-4 are scheduled from operational considerations to be on Launch+15 days and Encounter-20 days respectively. *Hence TCM-1 falls on 11/21/96 and TCM-4 on 08/22/97 for launch on 11/06/96. Correspondingly, TCM-1 is scheduled on 12/09/96 and TCM-4 on 09/01/97 for launching on 11/24/96.*

As already mentioned, TCM-2 is planned as a *blowdown maneuver* restricted to a maximum Δv of 6m/s. Moreover, TCM-1 and TCM-2 are considered as a pair of maneuvers to be designed under the strategy of a 2-impulse optimization to minimize total Δv. TCM-3 is always scheduled to follow TCM-2 after 30 days. This sequence of trajectory correction maneuvers will be considered **nominal throughout our discussion**.

With the planetary protection and *sun-angle constraint* conditions, together with the goal of minimizing the total Δv for the cruise phase of the mission, the *nominal mission calls for TCM-2 on 03/21/97 for launch date on 11/06/96 and on 03/24/97 for launch date on 11/24/96*. These schedules have been arrived at, after parametric studies on hundreds of cases. It may be remarked that for these two launch dates, TCM-2 is separated from TCM-1 by 120 and 105 days respectively.

Scheduling TCM-1 at different intervals after launch has also been examined, as seen in Tables 6.3 and 6.4. In these studies, the interval between successive trajectory correction maneuvers was maintained to be the same as for the nominal mission discussed in the paragraph above. The goal was to simply understand the penalty of delaying TCM-1 after launch. Also, in both tables, the unfavorable time for scheduling TCM-1 as indicated by CAPEL (Capability Ellipse) plots has been verified to be so by Monte Carlo analysis.

6.2.6 DISCUSSION OF INTERPLANETARY PHASE MANEUVER STATISTICS

In the present discussion, “nominal mission” will simply refer to the trajectory with launch date on either 11/06/96 or 11/24/96. TCM-1 is always scheduled 15 days after launch except where it is stated to be otherwise explicitly. TCM-2 will be scheduled 120 days after TCM-1 (actually on 03/21/97) for launch on 11/06/96. For launch date 11/24/96, TCM-2 will be 105 days after TCM-1 (on March 24, 97). In either case, TCM-1 and TCM-2 will be designed jointly under the 2-impulse optimization strategy. In particular, TCM-2 will be limited to a maximum of 6 m/s as a blowdown maneuver. TCM-3 is always scheduled 30 days past TCM-2 and TCM-4 will be executed 20 days before encounter. The “nominal mission” (when discussing the results in Tables 6.3 through 6.12) will always imply this sequence of trajectory correction maneuvers and design criteria. The sun-angle constraint and planetary quarantine condition are fully satisfied, except if stated otherwise.

The injection error covariance(s) for the “nominal mission” are obtained from Ref. 6.11, corresponding to the 3rd stage nominal spin rate of 70 RPM and nutation time constant of 30 sec. As already discussed, the covariance matrix is appropriately chosen depending on the launch date.

The results in the various tables are generally presented in the B-plane coordinate system. A complete description of the B-plane coordinate system can be found in Appendix 9.4 of this report.

Since the launch injection errors dominate the interplanetary phase maneuvers, it is convenient to begin with a discussion of the results from the figure of merit (FOM) analysis. The FOM is an upper bound to the required Δv to compensate for launch injection errors, in the absence of OD and maneuver execution errors and with no changes to the nominal trajectory for planetary protection requirements. From Table 6.2, it is seen that for the nominal mission, the FOM is 21.93 m/sec for the November 6, 1996 launch date and 25.33 m/sec for the 11/24/96 launch. These results are entirely consistent with the mean values of 17.24 and 18.23 m/sec for the total Δv required for all 4 correction maneuvers for these launch dates, when *planetary protection conditions are ignored* as for Cases 2 and 4 respectively in Table 6.5.

When planetary protection is taken into consideration, the mean values for the total of all 4 interplanetary TCMs, increase to 25.13 and 30.40 m/sec respectively, as seen for Cases 1 and 3 in Table 6.5, clearly indicating the Δv penalty of about 8 to 12 m/sec in the mean, for planetary quarantine. The 95th and 99th percentile values for the Δv required for the "nominal missions" for these two launch dates (Cases 1 and 3 in Table 6.5) are shown in Table 6.2 just for comparison.

TABLE 6.2. LAUNCH INJECTION ERRORS AND
A FIRST COMPARISON OF LAUNCH DATES 11/06/96 AND 11/24/96.
(Mars Global Surveyor Mission)

(Delta 7925 Third Stage Injection Errors from Ref. 6.11.)

(Spin Rate: 70 RPM. Nutation Time Constant: 30 sec.)

Launch Date	11/06/96	11/24/96
Mars Encounter	09/11/97	09/24/97
Injection Error Ellipse Characteristics		
σ(B·R), km	37,753	195,577
σ(B·T), km	419,919	532,420
σ(LTF), DAYS	5.8257	5.4726
Semi-Major Axis, km	420,106	565,947
Semi-Minor Axis, km	24,429	37,753
Orient. Angle, θ, deg	–3.935	19.867
Figure of Merit (FOM) and Delta-V Analysis		
Maneuver Date (TCM-1)	11/21/96	12/09/96
Elapsed Time, days (From Launch to TCM-1)	15	15
FOM, m/s	21.93	25.33
Cruise Delta-V[1], m/s	42.73[2]	53.53[2]
	53.28[3]	65.75[3]

[1]"Representative" case is described in the text.
[2]Entries are 95-th Percentile Total Delta-V.
[3]Entries are 99-th Percentile Total Delta-V.

Results of a more detailed FOM analysis for the launch date of November 6, 1996 are presented in Table 6.3. The largest value of 147.75 m/sec for the FOM obtained by scheduling TCM-1 on December 12, 1996 (36 days after launch) is shown just to emphasize the unfavorable timing of the maneuver, consistent with the results from CAPEL plots. In fact, it is interesting to note that the FOM values are just 21.93 and 26.33 m/sec if TCM-1 were to be scheduled on 11/21/96 or 11/27/96 - approximately 2 or 3 weeks before 12/12/96. Similarly, if TCM-1 were to be scheduled on 12/27/96 or 01/02/97 (or 15 and 21 days past the unfavorable maneuver date of 12/12/96), the FOM values decrease to 34.64 and 34.87 m/sec, simply confirming the CAPEL link results.

TABLE 6.3. FOM ANALYSIS AND SCHEDULING OF TCM-1.
(Mars Global Surveyor Mission)

(Launch Date: 11/06/96. Mars Encounter: 09/11/97.)

Delta 7925 Third Stage Injection Errors

(Spin Rate: 70 RPM. Nutation Time Constant: 30 sec.)

σ(B·R) = 37,753 km — Semi-Major Axis = 420,106 km
σ(B·T) = 419,919 km — Semi-Major Axis = 24,429 km
σ(LTF) = 5.8257 days — Orient. Angle, θ = –3.935º

Maneuver Schedule for FOM Computations			Representative[1] Cruise Delta-V, m/s	
Days From Launch	Calendar Date	FOM in m/s	95-th Percentile	99-th Percentile
10	11/16/96	19.85	40.51	49.88
12	11/18/96	20.57	41.28	51.34
15[2]	11/21/96	21.93	42.73	53.28
21	11/27/96	26.33	47.78	59.60
36	12/12/96	147.75[3]	>300	>500
51	12/27/96	34.64	66.64	84.76
57	01/02/97	34.87	70.51	89.64

[1] "Representative" case is described in the text.
[2] Nominal Schedule for Launch on 11/06/96.
[3] Unfavorable time for Maneuver indicated from CAPEL(K-Matrix Capability Ellipse) plots.

The representative total Δv values (actually 95th and 99th percentiles) for the interplanetary phase of the mission, when TCM-1 is scheduled on the different days as given in the first column of Table 6.3 are presented in the 4th and 5th columns. These values have been obtained by Monte Carlo analysis with the LAMBIC software (Ref. 6.15). The entries in the 4th and 5th columns of the 3rd row represent the Δv for the "nominal mission" discussed earlier, with launch on 11/06/96, TCM-1 scheduled 15 days after launch, TCM-2 on 3/21/97, TCM-3 on 04/20/97, TCM-4 on 08/22/97, and satisfying all the planetary protection conditions and sun-angle constraints; TCM-2 is limited to a maximum of 6 m/sec and jointly optimized together with TCM-1. These results are taken from the corresponding entries for Case 1 in Table 6.5.

Entries in the 4th and 5th columns of the other rows in Table 6.3, corresponding to scheduling TCM-1 on different days, have also been obtained from Monte Carlo analyses. Specifically, the maneuver schedules for the TCM's were changed, but no attempt was made to correct for any minor violation of the planetary protection condition or the sun-angle constraint. These results were obtained for comparison purposes only, to assess the penalties if there were any slip in the schedule. Obviously, the Monte Carlo analyses also confirm the unfavorable timing for maneuver as of December 12, 1996.

The detailed results of FOM analysis for the launch date (11/24) of the 1996 opportunity for the MGS mission, are shown in Table 6.4. The table is completely analogous to Table 6.3 for the 11/06/96 launch. In this case, the unfavorable timing for maneuver TCM-1 falls on December 22, 1996, 28 days past launch. Otherwise, the table is self-explanatory.

The most essential results on the Δv requirements for the interplanetary phase trajectory correction maneuvers are presented in Table 6.5. Both the November 6th and the November 24th launch dates (of 1996) are covered. For each launch date, the "nominal mission" as well as a comparative mission without the planetary protection conditions, are discussed. Cases 1 and 3 are the "nominal mission(s)" respectively for the launch dates 11/06/96 and 11/24/94. Correspondingly cases 2 and 4 are the missions, where the planetary quarantine conditions have been totally ignored. The Monte Carlo analyses for all 4 cases were carried out with the LAMBIC software already mentioned. The mean, standard deviation (1σ), the 95th and the 99th percentile Δv values are given in m/sec.

TABLE 6.4. FOM ANALYSIS AND SCHEDULING OF TCM-1.

(Mars Global Surveyor Mission)

(Launch Date: 11/24/96 Mars Encounter; 09/21/97.)

Delta 7925 Third Stage Injection Errors.

(Spin Rate: 70 RPM. Nutation Time Constant: 30 sec.)

σ(B·R) = 195,577 km Semi-Major Axis = 565,947 km

σ(B·T) = 532,420 km Semi-Major Axis = 37,753 km

σ(LTF) = 5.4726 days Orient. Angle, θ = 19.867º

Maneuver Schedule for FOM Computations			Representative[1] Cruise Delta-V, m/s	
Days from Launch	Calendar Date	FOM in m/s	95-th Percentile	99-th Percentile
10	12/04/96	21.60	47.91	59.17
12	12/06/96	22.79	49.94	61.24
15[2]	12/09/96	25.33	53.53	65.75
18	12/12/96	30.09	59.95	72.78
28	12/22/96	52.12[3]	90.77	117.49
35	12/29/96	31.29	63.98	80.67
42	01/05/97	31.95	67.40	86.06

[1]"Representative" case is described in the text.
[2]Nominal Schedule for Launch on 11/24/96
[3]Unfavorable time for Maneuver indicated from CAPEL plots.

TABLE 6.5. MGS MISSION INTERPLANETARY PHASE Δv STATISTICS.

(Delta 7925 Third Stage: Spin Rate: 70 RPM. Nutation Time Constant: 30 sec.)

		Delta-V Statistics in m/s			
		Mean	Std. Dev.	Δv	Δv
Maneuver	Date	μ	1σ	95%-ile	99%-ile
Launch Date - November 6, 1996.					
Case 1. Nominal Mission with PQ Restrictions and all Errors.*					
TCM-1	11/21/96	17.4554	9.67434	36.072	46.5640
TCM-2	03/21/97	5.4911	1.2103	6.000	6.0000
TCM-3	04/20/97	1.7915	.5437	2.564	2.6790
TCM-4	08/22/97	.3960	.1491	.656	.8252
TOTAL		25.1340	9.3096	42.730	53.2847
Case 2. Mission with NO PQ Restrictions. (Includes all Errors.*)					
TCM-1	11/21/96	14.0195	10.0839	33.255	43.3170
TCM-2	03/21/97	2.8577	2.0092	6.000	6.0000
TCM-3	04/20/97	.1194	.1982	.589	1.0632
TCM-4	08/22/97	.2425	.1326	.500	.6580
TOTAL		17.2390	10.2708	36.879	46.9654
Launch Date - November 24, 1996.					
Case 3. Nominal Mission with PQ Restrictions and all Errors.*					
TCM-1	12/09/96	22.9499	12.5291	45.892	58.0410
TCM-2	03/24/97	5.8000	.6325	6.000	6.0000
TCM-3	04/23/97	1.3396	.4649	2.087	2.2418
TCM-4	09/01/97	.3154	.1311	.551	.6879
TOTAL		30.4049	12.7863	53.533	65.7460
Case 4. Mission with NO PQ Restrictions. (Include. all Errors.*)					
TCM-1	12/09/96	15.2895	11.7755	38.178	50.6220
TCM-2	03/24/97	2.5648	1.7656	6.000	6.0000
TCM-3	04/23/97	.1278	.2644	.768	1.4418
TCM-4	09/01/97	.2475	.1377	.515	.6772
TOTAL		18.2295	11.7048	41.027	54.2615

*OD and Execution Errors at each maneuver included besides Launch Injection Errors.

In all 4 cases, TCM-2 has a 6.0 m/sec limit clearly imposed. The 95th percentile values for the TOTAL Δv are seen to be 42.73 and 53.53 m/sec for the Nov. 6th and 24th launch dates, clearly indicating the advantage of the earlier launch with a 10.8 m/sec savings in Δv. The corresponding Δv difference is nearly 12.5 m/sec at the 99th percentile.

The Δv cost of planetary protection conditions is clearly seen by comparing Cases 1 and 2 as well as Cases 3 and 4. For instance, for the Nov. 6th launch, (Cases 1 and 2) the mean values for total Δv are 25.13 and 17.24 m/sec with and without planetary quarantine; in short, planetary quarantine costs about 7.89 m/sec. In this case, the 95th and 99th percentile differences are 5.85 and 6.31 m/sec respectively.

The Δv cost of planetary protection is even higher for the launch on Nov. 24, 1996, as seen for Cases 3 and 4 in Table 6.5. The mean values for the total Δv are 30.40 and 18.23 m/sec respectively with and without planetary quarantine; in this case, the cost of planetary protection is 12.18 m/sec. At the 95th and 99th percentile levels, the Δv cost works out to 12.51 and 11.48 m/sec.

While mission design considerations rely substantially on the 95th or 99th percentile confidence levels, the mean values for the total Δv in Table 6.5 indicate the anticipated actual cost in terms of propellant(s). Thus the Δv penalty due to planetary quarantine is about 8m/sec for the launch on 11/06/96 and about 12 m/sec for the launch on 11/24/96. The additional Δv is necessary to progressively re-target the spacecraft towards the final desired aim-point, after deliberately biasing it away at launch, to limit the probability of the spacecraft impacting the planet to a value at or below 10^{-5}. This leads to a discussion of "biasing the aim-points" for planetary protection.

The detailed results of planetary quarantine analysis for the "nominal mission" with launch date on Nov. 6, 1996, are presented in Table 6.6. The (**B•R**) and (**B•T**) values for the final aim-point are (-7284, -396) km; however, at launch, the aim-point is biased to (-68530, -181306) km in order to limit the impact probability to $<10^{-5}$. The contour of the "probability ellipse" corresponding to a value of 10^{-5} is shown in Figs. 6.1 and 6.2 to different scales along with the biased launch aim-point and the 1-σ dispersion ellipse. The entries in the table are obtained from the statistics of the 5000 sample points in the Monte Carlo analysis of the "nominal mission". It may be remarked that at launch, if the spacecraft is directed towards the nominal final aim-point, the probability of the spacecraft impacting Mars is 0.23×10^{-2}.` Hence biasing is required to satisfy the planetary protection requirement at launch.

The B-plane delivery points and dispersion ellipse parameters for all the 4 trajectory correction maneuvers are shown in the table along with the probability of impact at each maneuver. On the assumption that following a maneuver, the next one fails with a probability of 10^{-2}, (except for TCM-4 Contingency), the cumulative probability that the spacecraft will impact on Mars is shown to be $<1.79 \times 10^{-4}$ for the "nominal mission" with launch date on Nov. 6, 1996.

Entries for TCM-1 in the 2nd row of Table 6.6 merit some explanation. The aim-point at TCM-1 is chosen by the software algorithm, optimizing TCM-1 and TCM-2 jointly. The bias at launch is considerably relaxed, although not entirely, in the (**B•T**) coordinate and to a lesser extent in (**B•R**). Since the delivery point is considerably farther away from the final aim-point, no further biasing is required and the impact probability is reduced to about 0.41×10^{-5}. It must be remarked that dispersion ellipse parameters in the 2nd row include the distribution of the aim-points in the B-plane with the OD and execution errors folded into the covariance. The dispersion values inside parentheses just below the main entries are the scatter values due to OD and maneuver execution errors about the design-aimpoint. The situation is shown plotted in Fig. 6.3.

Biasing is still required at TCM-2 and TCM-3; but the bias is progressively smaller in value, and at TCM-3, the bias is just about 125 km in (**B•R**) and 25 km in (**B•T**). The aim-point and the 1-σ dispersion ellipse, the contour for 10^{-2} impact probability, the planetary capture radius and the outline of Mars on the B-plane are all shown in Figs. 6.4 through 6.6, for the nominal mission launching on 11/06/96.

The detailed results on planetary quarantine analysis for the "nominal mission" with launch date 11/24/96 are presented in Table 6.7 and in Figs. 6.7 through 6.12. Because of the similarity of the results for the two cases, no detailed explanation will follow. In particular, for TCM-1 through TCM-4, even the scales for the corresponding plots are maintained the same, so that comparisons can easily be made. The most noteworthy departure is at launch; the launch injection error covariances for the two launch dates are remarkably different, particularly in the orientation of the ellipse (and hence the probability contour), as seen in Figs. 6.1 and 6.7 and correspondingly in Figs. 6.2 and 6.8. It may also be remarked that without biasing the aim-point at launch, the probability of the spacecraft impacting on Mars is 0.11×10^{-2} for the trajectory with launch date 11/24/96. (However, it must be noted that actually the injection error covariance matrix pertaining to the launch on 11/16/96 has been used throughout the analysis here, for the launch on 11/24/96.)

TABLE 6.6. LAUNCH AND INTERPLANETARY PHASE DELIVERY POINTS, DISPERSION ELLIPSE AND SPACECRAFT IMPACT PROBABILITY DATA.

Launch Date: November 6, 1996

Mars Encounter Date: September 11, 1997. Enc. Aim-Point: (B·R) = –7284.304 km; (B·T) = –396.498 km

Event	Delivery Point - km		Disp. Ellipse - km, deg			Prob. of Impact, *pi*	Next Mnvr. Fails, Prob. *qi*	S/C Impact Prob., *piqi*	Notes
	(B·R)	(B·T)	S-Major	S-Minor	Ori., θ				
Launch 11/06/96	–68,530	–181,306	420,106	24,429	–3.94	$0.99X10^{-5}$	10^{-2}	$0.99X10^{-7}$	Biased
TCM-1 11/21/96	–54,015	–76,022	43,489 (4183)	18,399 (421)	–18.42 (–4.66)	$0.41X10^{-5}$	10^{-2}	$0.41X10^{-7}$	Biased
TCM-2 03/21/97	–16,572	–6,509	6,039	4,629	21.08	$0.96X10^{-2}$	10^{-2}	$0.96X10^{-4}$	Biased
TCM-3 04/20/97	–7,478	–425	408	227	–7.68	$0.82X10^{-2}$	10^{-2}	$0.82X10^{-4}$	Biased
TCM-4 08/22/97	–7,284	–396	39	23	–86.40	$<10^{-10}$	10^{-2}	$<10^{-12}$	Nominal
TCM-4 Contingency 09/01/97	–7,284	–396	---	---	---	$<10^{-10}$	1	$<10^{-10}$	Nominal
							Subtotal	$<1.79X10^{-4}$	

TABLE 6.7. LAUNCH AND INTERPLANETARY PHASE DELIVERY POINTS, DISPERSION ELLIPSE AND SPACECRAFT IMPACT PROBABILITY DATA.

Launch Date: November 24, 1996

Mars Encounter Date: September 21, 1997. Enc. Aim-Point: (B·R) = –7273.631 km; (B·T) = –428.517 km

	Delivery Point - km		Disp. Ellipse - km, deg.						
Event	(B·R)	(B·T)	S-Major	S-Minor	Ori., θ	Prob. of Impact, *pi*	Next Mnvr. Fails, Prob. *qi*	S/C Impact Prob., *piqi*	Notes
Launch 11/24/96	–50,276	–201,814	565,947	37,753	19.87	0.99×10^{-5}	10^{-2}	0.99×10^{-7}	Biased
TCM-1 12/09/96	–59,235	2,330	46,516 (7159)	8,630 (722)	11.95 (1.55)	$< \times 10^{-5}$	10^{-2}	$< \times 10^{-7}$	Biased
TCM-2 03/24/97	–13,108	–3,872	5,910	3,310	35.69	1.22×10^{-2}	10^{-2}	1.22×10^{-4}	Biased
TCM-3 04/23/97	–7,596	–426	375	223	–4.64	1.00×10^{-2}	10^{-2}	1.00×10^{-4}	Biased
TCM-4 09/01/97	–7,274	–429	38	22	–75.77	$<10^{-10}$	10^{-2}	$<10^{-12}$	Nominal
TCM-4 Contingency 09/11/97	–7,274	–429	---	---	---	$<10^{-10}$	1	$<10^{-10}$	Nominal
							Subtotal	$<2.23 \times 10^{-4}$	

It has earlier been mentioned that the injection error covariance matrices, launch velocity deficiency probability distributions and the sensitivity of the spacecraft state at injection to launch velocity deficiency have been received over several months as the work was in progress. The final injection covariance matrices are due by November, 95. The currently used injection error covariance matrices for the 3rd stage (of the Delta 7925 launch vehicle) are given in Refs. 6.11 for a nominal spin rate of 70 RPM and nutation time constants of 30 and 80 seconds. The probability distribution for velocity deficiency for the 98.89% PCS (Probability of Command Shutdown) case along with the spacecraft state sensitivity coefficients are also given therein. The velocity deficiency distribution for the 95% PCS (due to second stage propellant depletion) can be obtained from Ref. 6.12. The launch injection errors for the November 6th and November 16th launch dates corresponding to a third stage nominal spin rate of 59.01 RPM and nutation time constant of 30 seconds are obtained from Ref. 6.13. From analyses pertaining to these error levels, it is desired to estimate the interplanetary Δv requirements for the MGS mission with a launch vehicle characterized by a nominal spin rate of 59 RPM and nutation time constant of 86 seconds; moreover, the additional Δv required to compensate for the launch velocity deficiency corresponding to both the 98.89% and 95% “probability of command shutdown” must be estimated also.

Hence “difference tables” for the Δv requirements due to these various physical phenomena are constructed from appropriate Monte Carlo analyses of the “nominal mission” modified as necessary, as for instance in the case of launch velocity deficiencies. The results of these various cases for the November 6th launch date are presented in Table 6.8. The entries in each row deal with changes in any one of these physical causes only. The first row corresponds to “the nominal mission” with 11/06/96 launch. It is seen that the total Δv required is 42.73 and 53.285 m/sec at the 95th and 99th percentile confidence levels exactly as for Case 1 in Table 6.5. In the third row, for instance, the injection velocity deficiency corresponding to 95% PCS (implying 5% of the launches result in deficiencies in spacecraft velocity as per the distribution in Ref. 6.12) is examined. The required Δv values are 48.364 and 82.348 m/sec at the 95th and 99th percentile levels; the ‘differences’ of +5.634 and +29.063 m/sec are entered appropriately. Similarly, from the entries in the second row, it is seen that corresponding to the 98.89% PCS level, the Δv differences are +1.372 and +2.460 m/sec, at the 95th and 99th percentile confidence levels respectively.

When the nominal spin rate of the Delta third stage decreases from 70 RPM to 59 RPM, the required Δv values are 49.195 and 62.266 m/sec at the 95% and 99% confidence levels, as seen from the entries in the 4th row. In this case, the nutation time constant is 30 seconds, just as for the nominal; furthermore, the probability of command-shutdown is 99.7%, implying no launch velocity deficiency, just as in the nominal case. Hence, the Δv penalties of +6.465 and +8.981 m/sec (at the 95th and the 99th percentile levels) can be strictly attributed to the change in the nominal spin rate as reflected in the injection covariance.

Comparing the entries in the 5th row and the nominal case in the 1st row, it is seen that an increase in the nutation time constant from 30 seconds to 80 seconds, decreases the Δv required by about 1.5 to 2 m/sec. In these two cases, the spin rate is held at 70 RPM and the PCS level at 99.7% and the change in Δv required is simply due to the difference in the launch injection covariance due to different nutation time constants.

Detailed results for changes in Δv from exactly the same physical causes for the November 24th launch date are presented in Table 6.9. It may be noted that the differences in the 95th and 99th percentile values of Δv are +5.519 and +38.315 m/sec due to launch velocity deficiency in the 95% PCS case. It is also observed in both tables, that as the nutation time constant increases from 30 to 80 seconds, the change in Δv required is negative indicating an “advantageous” trend. In both tables, entries in the last row correspond to the nominal mission, but without the planetary quarantine constraints, repeated here just for comparison.

In Tables 6.8 and 6.9, several cases have been discussed specifically to build the “difference tables”, for the changes in total Δv required, due to changes in any one of the three physical parameters, namely, the spin rate, the nutation time constant and the launch velocity deficiency due to PCS level change. The differences are attributable to changes in any one parameter at a time. *The MGS Project Office has indicated that a nominal spin rate of 59 RPM, with a nutation time constant of 86 seconds and velocity deficiency corresponding to 95% PCS level would quite likely characterize the launch conditions for the actual mission for the launch dates*, considered here. Hence, the anticipated values of Δv required, corresponding to this set of values of the launch uncertainties, are presented in Table 6.10 as “derived” from Tables 6.8 and 6.9, for both the November 6th and 24th launch dates. Otherwise, the entries in Table 6.10 are self-explanatory. *In particular, it must be noted that in Tables 6.8 through 6.12, the total Δv required for all four trajectory correction maneuvers are presented and discussed.*

TABLE 6.8. LAUNCH UNCERTAINTIES AND INTERPLANETARY DELTA-V COSTS.

Launch Date: November 6, 1996. Mars Encounter Date: September 11, 1997.

TCM-1: Launch + 15 days. TCM-2: Blowdown 6 m/s - 3/21/97.
TCM-3: TCM-2 + 30 days. TCM-4: August 22, 1997.

	Launch Characteristics			95th Percentile		99th Percentile	
Case	RPM	T[a] (sec)	PCS[b] %	ΔV_{95}	Change from Nominal, δ_{95}	ΔV_{99}	Change from Nominal, δ_{99}
				(All delta-V entries below are in m/s.)			
1	70	30	99.70	42.730	Nominal	53.285	Nominal
2	70	30	98.89	44.102	+1.372	55.745	+2.460
3	70	30	95.00	48.364	+5.634	82.348	+29.063
4	59	30	99.70	49.195	+6.465	62.266	+8.981
5	70	80	99.70	41.257	-1.473	51.066	-2.219
6	(Nominal w/out PQ)[c]			36.879	-5.851	46.965	-6.320

[a]Nutation Time Constant.
[b]Probability of Command Shut-down resulting in injection velocity deficiency.
[c]Included just for convenience in comparison.

TABLE 6.9. LAUNCH UNCERTAINTIES AND INTERPLANETARY DELTA-V COSTS.

Launch Date: November 24, 1996. Mars Encounter Date: September 21, 1997.

TCM-1: Launch + 15 days. TCM-2: Blowdown 6 m/s - 3/24/97.
TCM-3: TCM-2 + 30 days. TCM-4: September 1, 1997.

	Launch Characteristics			95th Percentile		99th Percentile	
Case	RPM	T^a (sec)	PCS^b %	ΔV_{95}	Change from Nominal, δ_{95}	ΔV_{99}	Change from Nominal, δ_{99}
				(All delta-V entries below are in m/s.)			
1	70	30	99.70	53.533	Nominal	65.746	Nominal
2	70	30	98.89	54.388	+0.855	67.868	+2.122
3	70	30	95.00	59.052	+5.519	104.061	+38.315
4	59	30	99.70	62.263	+8.73	77.322	+11.576
5	70	80	99.70	51.267	-2.266	62.452	-3.294
6	(Nominal w/out PQ)[c]			41.027	-12.506	54.262	-11.484

[a]Nutation Time Constant.
[b]Probability of Command Shut-down resulting in injection velocity deficiency.
[c]Included just for convenience in comparison.

TABLE 6.10. INTERPLANETARY MANEUVER TOTALS IN m/s.

Launch Date - November 6, 1996		
	ΔV95	ΔV99
Nominal (70 RPM, 30 s NTC, 99.7% PCS)	42.7	53.3
PCS 95%	+5.6	+29.0
Revised Spin and Nutation Time Constant (59 RPM, 86 s)	+4.8	+6.5
TOTAL	53.1	88.8

Launch Date - November 24, 1996		
	ΔV95	ΔV99
Nominal (70 RPM, 30 s NTC, 99.7% PCS)	53.5	65.7
PCS 95%	+5.6	+38.3
Revised Spin and Nutation Time Constant (59 RPM, 86 s)	+6.2	+7.9
TOTAL	65.3	111.9

The present navigation plan calls for a blowdown TCM-2 maneuver, limited to a maximum of 6 m/sec to facilitate improved spacecraft systems integrity. Of course, TCM-2 is jointly optimized with TCM-1. However, other options including 2-impulse optimization of TCM-1 and TCM-2 with a 45-day or a 90-day separation between the maneuvers have been examined without specifying a limit (such as 6 m/sec) on the Δv for TCM-2. So also, a K-inverse strategy with a chain of 3 maneuvers only, with TCM-1 correcting for the launch bias and injection errors, has been examined; in this case planetary protection is not considered after launch. So also, it has been of interest to examine the Δv savings, if the probability of the spacecraft impacting Mars is relaxed from 10^{-5} to 10^{-4} at launch. In particular, for all these cases, the total Δv required for the interplanetary phase of the MGS mission, corresponding to the (59 RPM, 86 sec NTC, 95% PCS) “launch conditions” for both the 11/06/96 and 11/24/96 launch dates are presented in Tables 6.11 and 6.12, as ‘derived’ from the values in Table 6.10, when appropriate.

The K-inverse strategy is seen as a poor choice in both cases. The 2-impulse optimization (without considering a 6 m/sec blowdown maneuver for TCM-2) with a separation of 90 days between TCM-1 and TCM-2, is equivalent to the 6m/sec blowdown TCM-2 with a separation of 120 days between the maneuvers, for the November 6, 1996 launch date. However, the 2-impulse optimization with 90-day separation is more advantageous than the blowdown maneuver option, for the November 24th launch, resulting in about 5 m/sec savings in total Δv (see entries in the 1st and 3rd rows of Table 6.12). 2-impulse optimization with a 45-day separation, is decidedly unfavorable for the November 6th launch, in comparison to the blowdown maneuver, by a Δv cost of about 9 to 10 m/sec; for the 11/24/96 launch, the Δv penalty is just about 2 m/sec at the 95th percentile level. Relaxing the planetary impact probability at launch from 10^{-5} to 10^{-4}, results in a Δv savings of about 3 to 9 m/sec depending on the launch date and TCM strategy.

TABLE 6.11. INTERPLANETARY MANEUVER OPTIONS AND ΔV EFFECTS.

(Including Relaxation of Planetary Impact Probability at Launch).

Launch Date: November 6, 1996. Mars Encounter Date: September 11, 1997.

TCM-1: Launch + 15 days. TCM-2: See Table below.

TCM-3: TCM-2 + 30 days. TCM-4: August 22, 1997.

59 RPM 86 s NTC

Case	Strategy	TCM-1 - TCM-2 Separation, days	delta-V, m/s 95-th Percentile	delta-V, m/s 99-th Percentile	δ(PQ): $10^{-5} \rightarrow 10^{-4}$ δ (delta-V) m/s
1	TCM-2: Blowdown Maneuver (Maximum - 6 m/s)	120	~53	~89	~–3
2	2-impulse Optimization of TCM-1 and TCM-2	45	~62	~99	~–4.5
3	2-impulse Optimization of TCM-1 and TCM-2	90	~53	~89	---
4	TCM-1: K-Inverse Strategy Corrects PQ Bias and Launch Injection Errors	30	~65	~102	---

TABLE 6.12. INTERPLANETARY MANEUVER OPTIONS AND ΔV EFFECTS.

(Including Relaxation of Planetary Impact Probability at Launch.)

Launch Date: November 24, 1996. Mars Encounter Date: September 21, 1997.

TCM-1: Launch + 15 days. TCM-2: See Table below.

TCM-3: TCM-2 + 30 days. TCM-4: September 1, 1997.

59 RPM 86 s NTC

Case	Strategy	TCM-1 - TCM-2 Separation, days	delta-V, m/s 95-th Percentile	delta-V, m/s 99-th Percentile	δ(PQ): $10^{-5} \rightarrow 10^{-4}$ δ (delta-V) m/s
1	TCM-2: Blowdown Maneuver (Maximum - 6 m/s)	105	~65	~112	~–9
2	2-impulse Optimization of TCM-1 and TCM-2	45	~67	~113	~–6
3	2-impulse Optimization of TCM-1 and TCM-2	90	~60	~107	–3.5
4	TCM-1: K-Inverse Strategy Corrects PQ Bias and Launch Injection Errors	30	~84	~129	---

6.2.7 SUMMARY - INTERPLANETARY STATISTICAL MANEUVER ANALYSIS STUDIES

The total Δv necessary for the MGS mission ranges from 53.1 and 65.3 m/sec at the 95th percentile to 88.8 and 111.9 m/sec at the 99th percentile confidence level depending on the launch date and launch injection uncertainties. It is understood that TCM-2 will be a “blowdown” maneuver as appropriate. These values are consistent with the results in Table 6.10 and the Project Office guidelines on launch injection uncertainties. The low value of 53.1 m/sec corresponds to the earlier launch date and at the 95th percentile confidence level. For a Delta rocket launch vehicle with a 3rd stage nominal spin rate of 59 RPM, a nutation time constant of 86 secs, and a statistical velocity deficiency profile corresponding to 95% PCS, the Δv required is approximately 112 m/sec at the 99th percentile level, for the launch date of 11/24/96. Two-impulse optimization of TCM-1 and TCM-2 (without a blowdown maneuver for TCM-2), with a 90-day separation between the two maneuvers, requires about the same Δv for the 11/06/96 launch and about 5 m/sec less for the 11/24/96 launch. Other strategies for the interplanetary trajectory correction maneuvers do not seem to be equally advantageous.

By biasing the aim-points at injection and at the first three trajectory correction maneuvers, the planetary protection requirements can be satisfied throughout the cruise phase.

The plan(s) for an interplanetary phase TCM strategy with two-impulse optimization with or without a “6 m/sec blowdown maneuver” for TCM-2, as recommended here, will meet the “payload sun avoidance requirements”. In fact, even the K-inverse strategy examined will meet all the PQ requirements and sun-angle constraint conditions, but will impose additional Δv penalty.

Updates to these results will be forthcoming, when the necessary final launch injection uncertainties are obtained.

It is explicitly recommended here that the values of Δv required for the interplanetary phase trajectory correction maneuvers for the MGS mission, be obtained from Table 6.10 in this report, rather than from other results discussed for the nominal mission in earlier paragraphs.

FIGURE 6.1 THROUGH FIGURE 6.12

PQ CONTOURS, AIMING POINTS AND DISPERSION ELLIPSES

FOR

INTERPLANETARY PHASE

6.3 ORBIT INSERTION PHASE MANEUVER ANALYSIS

The Mars orbit insertion phase extends from MOI in September of 1997 until the spacecraft is declared ready for mapping, by March of 1998. This long phase has 3 sub-phases entitled “Mars Capture,” “Aerobraking,” and “Transfer to Mapping.”

6.3.1 MARS CAPTURE

The orbit insertion (MOI) maneuver will insert the spacecraft into a 48 hr orbital period near periapsis. The main engine will fire for approximately 24-25 min to provide a slow down of roughly 985 m/s for a 3700 km elliptical periapsis radius.

The spacecraft will utilize a “pitch-over” steering strategy with a constant pitch rate for MOI of about 0.029 deg/s in order to maximize the efficiency of the burn. Depending on the exact launch date, the spacecraft will arrive at Mars between September 11, 1997 and September 22, 1997.

Due to dispersions, the spacecraft will not be in the desired 48 hr orbit after MOI. Tables 6.13 and 6.14 show the possible 3σ dispersions of the orbit due to various error sources. The dispersions of Table 6.13 utilize specification errors for maneuver execution, while those of Table 6.14 represent a lower bound, utilizing capability maneuver execution errors of Reference 6.5. The probable dispersion is between these two extremes.

TABLE 6.13. CAPTURE ORBIT UNCERTAINTIES
WITH SPECIFICATION MANEUVER EXECUTION ERRORS

		Uncertainty (3 sigma)			
Orbit Element	Target	OD	TCM-4*	MOI*	Total
Orbit Period (Hours)	48.0	3.2	---	9.2	9.7
Periapsis Altitude (KM)	300.0	73.0	56.0	4.1	92.1
Inclination (Deg)	92.87	0.30	0.34	0.13	0.47

*Assumes specification maneuver execution errors.

TABLE 6.14. CAPTURE ORBIT UNCERTAINTIES
WITH CAPABILITY MANEUVER EXECUTION ERRORS.

Orbit Element	Target	Uncertainty (3 sigma) OD	TCM-4*	MOI*	8% Thrust**	Total
Orbit Period (hr)	48.0	3.2	---	0.8	-1.0 +1.9	-3.4 +3.8
Periapsis Altitude (km)	300.	73.	5.8	1.1	-12.3 +5.4	-74.3 +73.4
Inclination (deg)	92.87	0.30	0.08	0.06	0	∓0.32

*Assumes capability maneuver execution errors.
**Worst possible thrust error.

6.3.2 AEROBRAKING

6.3.2.1 WALK-IN

The walk-in phase is about 22 days in duration and represents the initial phase of aerobraking, when the periapsis altitude is lowered in 4 steps using apoapsis maneuvers. The 4 maneuvers are designated AB1 (bipropellent), AB2 (mono), AB3 (mono), and AB4 (mono). Table 6.15 shows the approximate size of these maneuvers and target periapsis altitudes. The first of these maneuvers, AB1, will also correct the inclination error that resulted at MOI. The total Δv during the phase is about 7.5 m/s.

TABLE 6.15. WALK-IN PHASE MANEUVER INFORMATION.

		Launch Date: 11/05/96 - 11/25/96		
Maneuver Event	Event Time in Days from MOI	Maneuver Magnitude m/s	Target Periapsis Radius km	Periapsis Radius Change for Maneuver km
MOI	0	983.4 to 987.2	3700	---
AB1	9	6.52 to 6.35* (± 1.15 1σ)	3525.8 to 3530.3	-174.2 to -169.7
AB2	17 AB1 + 8 days	.75 to .80	3505.9 to 3509.0	-19.9 to -21.3
AB3	23 AB1 + 14 days	.20 to .18	3500.5 to 3504.2	-5.4 to -4.8
AB4	31 AB1 + 22 days	.042 to .08	3499.4 to 3502.1	-1.1 to -2.1

*Includes a .07 m/s deterministic effect of also correcting the post MOI inclination with the AB1 maneuver.

6.3.2.2 MAIN PHASE

The main phase of aerobraking is about 75 to 81 days in duration. The main phase is defined by the use of small propulsive maneuvers (ABM's), executed at apoapsis, to maintain periapsis within a well-defined periapsis altitude corridor. The corridor will be low enough to produce the necessary drag for a lowering of the apoapsis altitude to the desired value, yet high enough to avoid spacecraft heating limits. Due to the oblateness of Mars, the altitude of periapsis tends to rise during the main phase, so that ABM's will be in the "down" direction to lower periapsis. A total of about 19 maneuvers will be performed during this phase, producing a total translational Δv of about 3 to 4 m/s during the main phase. Figures 6.13 and 6.14 show the argument of periapsis and the maneuver sizes during aerobraking.

6.3.2.3 WALK-OUT

The walk-out phase is 14 to 22 days in duration and represents the final stage of aerobraking, when the apoapsis altitude rapidly approaches the desired value of 450 km. The periapsis altitude is raised with daily ABM's to decrease the dynamic pressure in order to maintain a 3 day orbit decay recovery period. Approximately 13-20 maneuvers will be performed for a total translational Δv of about 15 to 23 m/s, depending on launch date. The total translational Δv used during the whole aerobraking period (for 3 phases) is 26 to 34 m/s, depending on launch date. Table 6.16 gives aerobraking phase maneuver information.

At the end of walk-out, a final maneuver (ABX) is to be performed to raise the periapsis radius to approximately 3780 km. The total Δv needed is about 57 m/sec. A small inclination error, accumulated during aerobraking, will also have to be corrected and might be performed in conjunction with this maneuver in order to keep the Δv penalty low. For a 0.1 deg. (1σ) inclination error, the additional expected cost at ABX is approximately one meter per second. However, if the maneuver is performed later, to solely correct inclination after mapping orbit insertion, the expected magnitude is about 4.7 m/s with an uncertainty of $\pm$ 3.5 m/s (1σ).

TABLE 6.16. AEROBRAKING PHASE MANEUVER INFORMATION.

Parameter	Open of Launch Period Case	Close of Launch Period Case
Launch Date	5 November 1996	25 November 1996
Arrival Date	11 September 1997	22 September 1997
Number of Aerobrake Orbits	482	385
Aerobrake Completion Date	23 January 1998	19 January 1998
Walk-in	22 days in duration	22 days in duration
Main Phase	81 days in duration	75 days in duration
Walk-out	23 days in duration	14 days in duration
Total	126 days in duration	111 days in duration
Mean Local Solar Time (hrs)	14.06	13.97
Periapsis Latitude	9º south	33º north
Apoapsis Altitude	450 km	450 km
Periapsis Altitude	143 km	144 km
Propulsive ΔV (m/s)		
Walk-in	7.51	7.41
Main Phase	3.83	3.14
Walk-out	22.60	15.10
Total	33.94	25.65

6.3.3 TRANSFER TO MAPPING

The transfer to mapping is the final sub-phase of the orbit insertion phase. Approximately 25-40 days are required for the periapsis to rotate to the desired position over the south pole. During this time period, gravity calibration will be carried out to better determine the gravity field of Mars. Figure 6.15 shows the radius of periapsis and argument of periapsis vs. time for a 25 day time period to reach a 270º argument of periapsis. Once the 270º argument of periapsis is reached, a 17 m/s maneuver will be performed (TMO) near periapsis to transfer into the desired frozen orbit. As discussed in Section 6.4, a subsequent maneuver may be needed about 12 days later to refreeze the mapping orbit, based on the gravity calibration data.

FIGURE 6.13. ARGUMENT OF PERIAPSIS vs. TIME DURING AEROBRAKING.

FIGURE 6.14. PROPULSIVE MANEUVERS DURING AEROBRAKING.

FIGURE 6.15. PERIAPSIS AND APOAPSIS RADII AND ARGUMENT OF PERIAPSIS vs. TIME FOR TRANSITION TO MAPPING PHASE.

6.4 MAPPING PHASE MANEUVER ANALYSIS

6.4.1 INTRODUCTION

This section discusses the rationale and analysis for orbit trim maneuvers (OTMs) to maintain the mapping orbit. The orbital elements of the mapping orbit will deviate from the nominal values throughout the 687 day mission because of perturbations due to gravity field anomalies, maneuver execution errors and Mars atmospheric drag. OTMs will be necessary to keep the orbit elements within acceptable limits of the frozen orbit.

6.4.2 EFFECT OF GRAVITY FIELD ERRORS ON ESTABLISHMENT OF MAPPING ORBIT

The initial targeted frozen orbit will not be precisely frozen because of gravity field errors and thus small deviations in the semi-major axis and eccentricity should be expected. After the gravity field is refined, the new mean target eccentricity of the frozen mapping orbit may differ from the current nominal value of 0.007 by $\pm$ 0.006 (3σ). A subsequent OTM will then retarget to the new eccentricity.

After a few weeks of data processing, during the 25-40 day transition period to the mapping orbit, the gravity field can be refined such that the new target eccentricity can be established. Once the gravity field is determined, the orbit will be propagated forward for about 70 days to obtain the e - ω plot and thus the proper target eccentricity. The plot of e vs. ω is that of an approximate ellipse with a complete cycle of about 70 days. The center of the ellipse is the target value to re-freeze the mapping orbit.

6.4.3 NOMINAL MAPPING STRATEGY

The baseline Mars Global Surveyor frozen mapping orbit provides for the equator crossing on each orbit to be separated by 28.62° (1697 km), thus allowing a near repeat every 7 Martian days (sols) or 89 revs. In fact the nominal groundtrack moves or walks 58.6 km eastward every 7 sols and thus fill-in the 28.62° equator crossing gap in about 26 sols. The 26 sol period is designated the mapping cycle.

6.4.4 GROUNDTRACK WALK SENSITIVITY

The walk interval is quite sensitive to the semi-major axis. For each 0.2 km average change in the semi-major axis, the walk interval (each 89 revs) changes by about 11.9 km. The walk interval affects the duration of the mapping cycle and the size/frequency of gores between adjacent groundtracks for some instruments.

6.4.5 SEMI-MAJOR AXIS UNCERTAINTY

Dispersions in the semi-major axis can be caused by atmospheric drag and by the Mars gravity field. Also, each time a trim maneuver is executed to alter or correct the orbital elements, a maneuver execution error results which perpetuates a small error in the semi-major axis. A current requirement exists to maintain the semi-major axis within + 0.7/-1.2 km throughout the mission.

This semi-major axis requirement was derived from ID and SRD requirements: “Groundtrack separation between successive repeat periods orbits of 1/3 to 1/20 orbit altitude.” A more stringent TES science requirement of complete coverage of the planet with 9 km instrument’s field-of-view can also be derived from page 3-3, Ref. 2.2. For Mars Observer, the 9 km complete coverage of the planet was not guaranteed as being achievable by Mission Design and Navigation. Options for trying to satisfy this possible requirement are discussed in Section 6.4.7.

6.4.5.1 MARS ATMOSPHERIC DRAG

Atmospheric drag affects the groundtrack walk interval by reducing the orbit semi-major axis. The mapping phase of the mission begins in early 1998, after Mars perihelion. Figure 6.16 shows the mean (50^{th} percentile, or 50%), 95%, 99%, and 99.9% high levels of atmospheric density (long-term plus short-term effects) over a 5 year period for a 378.1 km index altitude orbit with a nominal mean eccentricity of 0.007 and one higher eccentricity. The maximum expected density occurs in late 2001 when Mars passes through one of its perihelions (highest solar impact and dust storm activity). The lowest density occurs near each aphelion. From the figure the average 3σ high density for the nominal 687 day mission is about 2.2 X 10^{-13} kg/m^3 and 1.2 X 10^{-12} kg/m^3 for a 5 year mission. Figure 6.17 shows the decrease in the orbit semi-major axis that would occur during 1 Earth day if not corrected by an OTM. The figure is plotted against Mars atmospheric density for a spacecraft ballistic coefficient of 21 kg/m^2. For a different ballistic coefficient, the daily change in the semi-major axis would equal that from the plot multiplied by $\frac{21}{(bc)}$, where (bc) is the actual ballistic coefficient. The total change of the semi-major axis after N days, if not corrected, would then be N multiplied by the daily drag (in the figure), for a given assumed atmospheric density.

6.4.5.2 MANEUVER EXECUTION ERRORS

Our ability to maintain the semi-major axis depends on the maneuver execution accuracy and on the O.D. capability. The 3σ specification accuracy of the orbit trim maneuver magnitude is 0.05 m/sec, which corresponds to 0.11 km semi-major axis control (3σ). The OD capability appears to be a fraction of this value after Gravity Calibration.

6.4.6 ASCENDING NODE CONTROL

A current requirement exists to control the ascending node to within ±3° of the nominal location for the duration of the mission. This requirement may necessitate a few small maneuvers over the 687 day mission lifetime to control the node. The optimum manner to control the ascending node is to perform a small inclination correction to the orbit, which in turn alters the nodal rate change$\left(\dot{\Omega}\right)$. A correction in inclination of 0.1° will change the nodal rate by 0.018 deg/day and change the node by 12.4° in 687 days. A 5.9 m/sec maneuver is needed to change the inclination by 0.1°.

6.4.7 GROUNDTRACK EVOLUTION

6.4.7.1 LONGITUDE GRID CONTROL (LGC)

There is no requirement on this mission for Longitude Grid Control. The project adopted LGC for the previous M.O. mission in order to solve the orbit prediction problem in sequence planning. For LGC the spacecraft was targeted to pass over predefined equator longitude crossings (or longitude grid). The grid design was based on the nominal mapping orbit repeat pattern. LGC required OTMs which adjusted the orbit semi-major axis at regular intervals in order for the spacecraft ground traces to stay on the grid.

The requirement on M.O. was to control the mapping orbit such that the accuracy of equator crossings relative to the defined grid was ±30 km (99%) and to maintain the time of equator crossings within ±2 min (99%) of the times predicted in the grid specification. Removing the requirement for LGC for Mars Global Surveyor simplifies the operations of the mapping phase and reduces the number of OTMs.

6.4.7.2 GROUNDTRACK COVERAGE

Some type of groundtrack control may still be necessary to satisfy or partially satisfy the TES science request of complete coverage of the planet within 9 km instrument field-of-view. This requirement could not be completely satisfied for the previous Mars Observer Mission, even utilizing LGC.

6.4.7.2.1 Groundtrack Control Accuracy

Figure 6.18 shows the groundtrack control accuracy (99%) for Mars Global Surveyor if nominally performing monthly maneuvers over the course of the mission. Two plots are shown, one for a minimum maneuver size of 0.05 m/sec, which is the current specification, and the other for 0.01 m/sec, which might be achievable in flight.

The plots are very similar in shape to the atmospheric density plots of Figure 6.17 The smallest values occur within a year into the mapping mission and are attributed to the lower atmospheric densities at that time. Note that longitude control of less than 30 km (99%) could be achieved for about the first 15 months of the mapping mission with monthly maneuvers. The control peaks at about 200 km (99%) about 22 months into the mapping mission where the atmospheric density is the highest.

6.4.7.2.2 Groundtrack Coverage

Even with the good groundtrack control of above using monthly maneuvers, complete global coverage for TES, with no gaps, probably cannot be achieved over the 687 day mission (approximately 8400 orbits). Figure 6.19 shows the expected number of groundtrack separations at the equator that are greater than 9 km, on the lighted side of the planet. After 687 days of monthly maneuvers, about 68 groundtracks will still be separated by more than 9 km at the equator, assuming a minimum maneuver size of 0.05 m/sec; about 23 gaps will exist for a minimum maneuver size of 0.01 m/sec. These results are preliminary and probably good to within $\pm$ 50%.

If no maneuvers are performed to control the groundtracks, the top plot in Figure 6.19 shows the approximate number of groundtrack separations that are greater than 9 km at the descending equator crossings. Note that after 687 days the expected number of gaps is approximately 225. Approximately one-third of the 225 gaps (75) will have groundtrack separations between 9 and 10 km. The percentage of gaps will continue to decrease with increasing groundtrack separations. The largest single gap will have an expected ground track separation of approximately 15 km.

The project office will decide if the decrease in the expected number of groundtrack gaps from 225 to the 23-68 range is sufficient to warrant monthly maneuvers during the mapping mission. If the decision is to perform monthly maneuvers, then it is strongly recommended that they be delayed until after solar conjunction.

6.4.8 MANEUVER FREQUENCY TO CONTROL SEMI-MAJOR AXIS

If a decision is made not to control the groundtrack evolution by maneuvers, then maneuvers must still be performed occasionally to control the semi-major axis to within the required limits.

A requirement exists that maneuvers be no more frequent than every two weeks for the mapping orbit maintenance. Maneuver frequencies of a month or more are desirable. This should be no problem, according to Figure 6.16. For an average 3σ high density of 2.2 X 10^{-13} kg/m^3 for the 687 day mission, the average 3σ high maneuver frequency would be about 104 days to control the semi-major axis to within 1.2 km of the nominal. For the 5 year mission, the average 3σ high density is about 1.2 X 10^{-12} kg/m^3.

6.4.9 ΔV FOR THE MAPPING PHASE

The total Δv for the mapping phase can be obtained by taking the statistical combination (add means and RSS sigmas) of the Δv needed because of the various error sources.

6.4.9.1 ΔV FOR GRAVITY ANOMALIES

Figure 6.20 shows a conservative estimate of the total Δv needed to freeze the mapping orbit at OTM-1 for different assumptions about the needed change in eccentricity (see Section 6.4.2). The eccentricity may have to be changed by $\pm$ 0.006 (3σ) in order to freeze the mapping orbit. This maneuver will have a mean size of 5.3 m/sec, sigma of $\pm$ 4 m/sec, which corresponds to a 3σ high of 20 m/sec (99.9%) in Figure 6.20.

6.4.9.2 ΔV FOR ASCENDING NODE CONTROL

A few small maneuvers may be needed over the lifetime of the mission to maintain the node to within acceptable limits. Based on the Mars Observer experience, the total of these maneuvers should be less than a few m/sec.

6.4.9.3 ΔV FOR ATMOSPHERIC DRAG

Figure 6.21 shows the total Δv as a function of atmospheric density for a 687 day mapping mission and for a 5 year mission, to compensate for drag. The average 3σ high atmospheric density for the 687 day mission is about 2.2 X 10^{-13} kg/m^3 which corresponds to an average 3σ high Δv of about 3.5 m/sec from Figure 6.21 The average 3σ high atmospheric density for a 5 year mission is about 1.2X10^{-12} kg/m^3, which corresponds to an average 3σ high Δv of about 49 m/sec from Figure 6.21 or about 22 m/sec for a 99% high density. This mean Δv would then be about 2 m/sec with a 1σ uncertainty of about 4 to 5 m/sec for the 5 year missions.

6.4.10 LOCATION OF MANEUVERS TO CHANGE THE ORBITAL ELEMENTS IN MAPPING ORBIT

The optimum location of a maneuver in the orbit depends on the orbital elements which are to be changed. This section discusses the optimum locations for changing the orbital elements.

6.4.10.1 SEMI-MAJOR AXIS (a) CHANGE

To change the semi-major axis of the orbit, the maneuver could be placed anywhere around the orbit. The Δv would be applied along or opposite the velocity vector of the spacecraft. A 1 m/sec velocity increase will increase the semi-major axis by about 2.24 km. This can be computed from

$$\Delta a = \frac{2a^2 V}{\mu} \Delta V$$

where

a = semi-major axis of orbit
V = velocity of spacecraft, and
μ = gravitational constant.

For a near-circular orbit (small eccentricities),

$$\Delta a = \frac{2a}{V} \Delta V$$

6.4.10.2 ECCENTRICITY (e) CHANGE

To produce a change in eccentricity with no net change in the semi-major axis, the velocity Δv must be directed perpendicular to the velocity vector anywhere around the orbit ($\Delta V_{\perp}$). The maximum change in eccentricity for a given perpendicular velocity increment can be accomplished at a true anomaly of about 90 or 270 degrees, as shown in Figure 6.22 (actually, the optimum true anomaly occurs at ta = arccos [-e]). The plot shows the eccentricity change for a 1 meter per second velocity change ($\Delta V_{\perp}$) around the orbit. Note that the eccentricity can be changed by about + 0.0003 per m/sec in velocity increment. The eccentricity change can be approximated from

$$\Delta e = \frac{\sin(ta)}{V} \Delta V_{\perp}$$

for a near-circular orbit, where ta = true anomaly.

Applying a velocity change along the velocity vector produces an eccentricity change that can be approximated by

$$\Delta e = \frac{2 \cos(ta)}{V} \Delta V$$

for a near-circular orbit.

However, a change in the semi-major axis will result from the velocity correction.

6.4.10.3 ARGUMENT OF PERIAPSIS (ω) CHANGE

The rotation of the argument of periapsis can be accomplished by applying the velocity correction maneuvers in almost any direction (in the orbital plane). However, in order not to change the semi-major axis, the maneuver must be applied perpendicular to the velocity vector ($\Delta V_{\perp}$). The apsidal change can be approximated from

$$\Delta\omega \sim \frac{-\cos(ta)}{ev} \Delta V_{\perp}, \text{ in radians}$$

This apsidal change is plotted in Figure 6.23 for a 1 m/sec velocity correction (Δv) for varying eccentricities. Note that the maximum change in the rotation of the argument of periapsis can be accomplished at periapsis or apoapsis. Also, no rotation results for maneuvers directed perpendicular to the velocity vector near true anomalies of 90 or 270 degrees (actually no rotation occurs at a true anomaly of ta = arccos [-e]).

Applying a velocity change along the velocity vector produces a larger change in the apsidal rotation and can be approximated from

$$\Delta\omega \sim \frac{2\sin(ta)}{ev} \Delta V, \text{ in radians}$$

Note that the maximum change occurs near a true anomaly of 90 or 270 degrees. However, a change in the semi-major axis will result from the velocity correction.

6.4.10.4 INCLINATION (i) CHANGE

The inclination may have to be corrected several times during the mapping mission in order to control the node.

The optimum place to correct the inclination is where the spacecraft crosses the equator near a true anomaly of 90 or 270 degrees. The inclination can be changed by about 0.017 degree for a 1 m/sec maneuver perpendicular to the orbit plane. A 0.1° inclination change would then require 5.9 m/sec.

$$\Delta i \sim \pm \frac{\Delta V_N}{V}, \text{ in radians}$$

where ΔV_N is applied normal to the trajectory plane.

6.4.10.5 LINE OF NODES (Ω) CHANGE

The line of nodes is not changed instantaneously by performing the inclination maneuver at the equator. However, this is altered with an inclination maneuver, which changes the node with time. This is the preferred way to control the node because of the small Δv required.

Changing the line of nodes instantaneously is an expensive maneuver and will cost 1 m/sec for each 0.017 deg of change performed near the poles. Thus a 1 degree change in the line of nodes would require a 59 m/sec Δv maneuver perpendicular to the orbit plane.

$$\Delta\Omega \sim \pm \frac{\Delta V_N}{V \sin i}, \text{ in radians}$$

FIGURE 6.16. ORBIT AVERAGED ATMOSPHERIC DENSITY.

FIGURE 6.17. DAILY DECAY IN SEMI-MAJOR AXIS DUE TO ATMOSPHERIC DRAG.

FIGURE 6.18. PRELIMINARY 99% GROUNDTRACK CONTROL VS. MAPPING TIME.

FIGURE 6.19. PRELIMINARY EXPECTED NUMBER OF GROUNDTRACK SEPARATIONS GREATER THAN 9 km VS. MAPPING TIME.

FIGURE 6.20. DELTA-V TO CHANGE ECCENTRICITY.

FIGURE 6.21. TOTAL DELTA-V FOR DRAG COMPENSATION.

FIGURE 6.22. CHANGE IN ECCENTRICITY FOR PERPENDICULAR VELOCITY CORRECTION.

FIGURE 6.23. CHANGE IN ARGUMENT OF PERIAPSIS FOR PERPENDICULAR VELOCITY CORRECTION.

6.5 Interplanetary Maneuver Analysis Update

Since the publication of the final Nav Plan (9/15/95), the final Delta third stage injection covariances have been calculated by McDonnell Douglas and sent to JPL. The Delta third stage spin rate was finally estimated to be 59 RPM with a nutation time constant of 55 sec. The injection errors were less than published in the final Nav Plan, and this produced interplanetary ΔV_{95} values less than those published in the Nav Plan. Updated Table 6.2 reflects those changes for injection dispersions. The data labeled the Nov. 6 launch was actually calculated for a Nov. 5 launch. There are insignificant differences in the maneuver data between these two dates.

Also the planetary protection requirement for the third stage has been relaxed from 10^{-5} to 10^{-4} for a Mars impact. This enabled the launch biased aiming points to be moved in closer to Mars and to thus reduce the interplanetary ΔV more. Some ΔV savings are produced by the new smaller injection dispersions mentioned above. The planetary protection requirements are discussed in Section 6.2.2. Updated Table 6.5 shows the new ΔV values for each TCM and for the total interplanetary phase, assuming a PCS of 99.7% (probability of second stage shutoff).

The actual PCS varies with launch date. For Nov. 6, the PCS is 98.6% and 97.9% for the first and second launch times respectively. For Nov. 25, the PCS is 97.3% for the single launch time. The total interplanetary ΔV increases as the PCS decreases as indicated in Table 6.8 of Section 6.2.6. For a PCS of 98%, the ΔV_{95} is expected to increase by approximately 2 m/sec and for a PCS of 97% by approximately 3 m/sec from those shown in updated Tables 6.2 and 6.5. Thus the total interplanetary ΔV_{95} for Nov. 6 is approximately 38-39 m/sec and 51 m/sec for Nov. 25 launch.

In the new maneuver analysis above, TCM-2 is still limited to a maximum ΔV of 6 m/sec and will be a blowdown maneuver. This maneuver will nominally be performed 120 days after TCM-1. However variations of a few weeks either way may be necessary to optimize the maneuver in flight to obtain the smallest ΔV total or to insure that the payload sun avoidance constraint on the maneuver is satisfied.

New updated Tables 6.6 and 6.7 are shown: Note that the new total spacecraft probability of Mars impact ($p_i q_i$) for the interplanetary phases lies between 1.0×10^{-4} and 2.0×10^{-4}, which is adequate. A discussion of planetary protection requirements is in Section 6.2.2.

UPDATE

TABLE 6.2. LAUNCH INJECTION ERRORS AND
A FIRST COMPARISON OF LAUNCH DATES 11/06/96 AND 11/25/96.

(Mars Global Surveyor Mission)

Launch Date	11/06/96	11/25/96
Mars Encounter	09/11/97	09/22/97
Injection Error Ellipse Characteristics		
σ(B·R), km	42,607	198,204
σ(B·T), km	405,604	522,008
σ(LTF), days	5.5616	5.1407
Semi-Major Axis, km	407,307	557,425
Semi-Minor Axis, km	20,752	32,463
Orient. Angle, θ, deg	–5.249	20.571
Figure of Merit (FOM) and Delta-V Analysis		
Maneuver Date (TCM-1)	11/21/96	12/10/96
Elapsed Time, days (from launch to TCM-1)	15	15
FOM, m/s	19.601	22.906
Cruise Delta-V[1], m/s	36.975[2] 46.552[3]	47.901 59.068

[1]"Representative" case is described in the text.
[2]Entries are 95-th Percentile Total Delta-V.
[3]Entries are 99-th Percentile Total Delta-V.

UPDATE

TABLE 6.5. MGS MISSION INTERPLANETARY PHASE ΔV STATISTICS.

		Delta-V Statistics in m/s			
Maneuver	Date	Mean μ	Std. Dev. 1σ	ΔV 95%-ile	ΔV 99%-ile
Launch Date: November 6, 1996.					
Case 1. Nominal Mission with PQ Restrictions and all Errors.*					
TCM-1	11/21/96	15.001	9.361	32.994	42.608
TCM-2	03/21/97	4.051	1.578	5.720	6.000
TCM-3	04/20/97	0.087	0.045	0.151	0.189
TCM-4	08/22/97	0.263	0.138	0.527	0.679
TOTAL		19.401	9.059	36.975	46.552
Case 2. Mission with NO PQ Restrictions. (Includes all Errors.*)					
Not Available					
Launch Date: November 25, 1996.					
Case 3. Nominal Mission with PQ Restrictions and all Errors.*					
TCM-1	12/10/96	21.059	11.543	41.683	52.751
TCM-2	04/09/97	5.590	0.591	6.000	6.000
TCM-3	05/09/97	0.197	0.112	0.359	0.658
TCM-4	09/02/97	0.262	0.130	0.503	0.635
TOTAL		27.109	11.710	47.901	59.068
Case 4. Mission with NO PQ Restrictions. (Include. all Errors.*)					
Not Available					

*OD and Execution Errors at each maneuver included besides Launch Injection Errors.

UPDATE

TABLE 6.6. LAUNCH AND INTERPLANETARY PHASE DELIVERY POINTS, DISPERSION ELLIPSE AND SPACECRAFT IMPACT PROBABILITY DATA.

Launch Date: November 6, 1996

Mars Encounter Date: September 11, 1997. Enc. Aim-Point: (B·R) = –7297. km; (B·T) = –396. km

Event	Delivery Point - km		Disp. Ellipse - km, deg			Prob. of Impact, p_i	Next Mnvr. Fails, Prob. q_i	S/C Impact Prob., $p_i q_i$	Notes
	(B·R)	(B·T)	S-Major	S-Minor	Ori., θ				
Launch 11/06/96	–46,508	–84,260	407,307	20,752	–5.25°	$1X10^{-4}$	10^{-2}	$1X10^{-6}$	Biased
TCM-1 11/21/96	–32,936	–27,462	39,910 (3762)	15,454 (397)	–13.80° (–5.81°)	$0.18X10^{-2}$	10^{-2}	$0.18X10^{-4}$	Biased
TCM-2 03/21/97	–7,750	–650	749	363	–2.54°	$0.79X10^{-2}$	10^{-2}	$0.79X10^{-4}$	Biased
TCM-3 04/20/97	–7,352	–440	358	190	+0.96°	$1.03X10^{-2}$	10^{-2}	$1.03X10^{-4}$	Biased
TCM-4 08/22/97	–7,297	–396	35	22	–72.12°	$<10^{-10}$	10^{-2}	$<10^{-12}$	Nominal
TCM-4 Contingency 09/01/97	–7,297	–396	---	---	---	$<10^{-10}$	1	$<10^{-10}$	Nominal
							Subtotal	$<2.0X10^{-4}$	

UPDATE

TABLE 6.7. LAUNCH AND INTERPLANETARY PHASE DELIVERY POINTS, DISPERSION ELLIPSE AND SPACECRAFT IMPACT PROBABILITY DATA.

Launch Date: November 25, 1996

Mars Encounter Date: September 22, 1997. Enc. Aim-Point: (B·R) = –7277. km; (B·T) = –431. km

	Delivery Point - km		Disp. Ellipse - km, deg.						
Event	(B·R)	(B·T)	S-Major	S-Minor	Ori., θ	Prob. of Impact, p_i	Next Mnvr. Fails, Prob. q_i	S/C Impact Prob., $p_i q_i$	Notes
Launch 11/25/96	–63,440	+41,474	557,425	32,463	20.571º	1.00×10^{-4}	10^{-2}	1.00×10^{-6}	Biased
TCM-1 12/10/96	–50,463	+26,483	33,669 (6640)	4,980 (710)	–0.94º (1.645º)	$<10^{-10}$	10^{-2}	$<10^{-10}$	Biased
TCM-2 04/09/97	–8,873	–390	1,188	691	–22.17º	0.31×10^{-2}	10^{-2}	0.31×10^{-4}	Biased
TCM-3 05/09/97	–7,378	–525	338	206	–0.254º	0.87×10^{-2}	10^{-2}	0.87×10^{-4}	Biased
TCM-4 09/02/97	–7,277	–431	35	22	–74.17º	$<10^{-10}$	10^{-2}	$<10^{-12}$	Nominal
TCM-4 Contingency 09/12/97	–7,277	–431	---	---	---	$<10^{-10}$	1	$<10^{-10}$	Nominal
							Subtotal	$<1.19 \times 10^{-4}$	

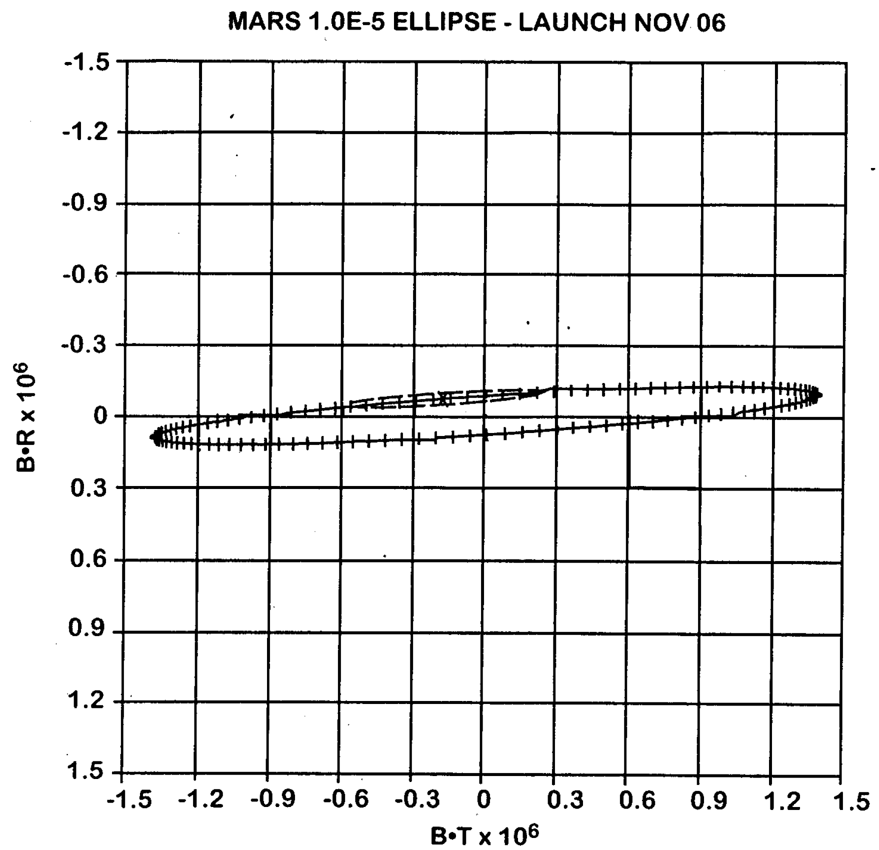


Figure 6.1
PQ Contour, Aim-point and (1-sigma) Dispersion Ellipse at Launch, 11/06/96

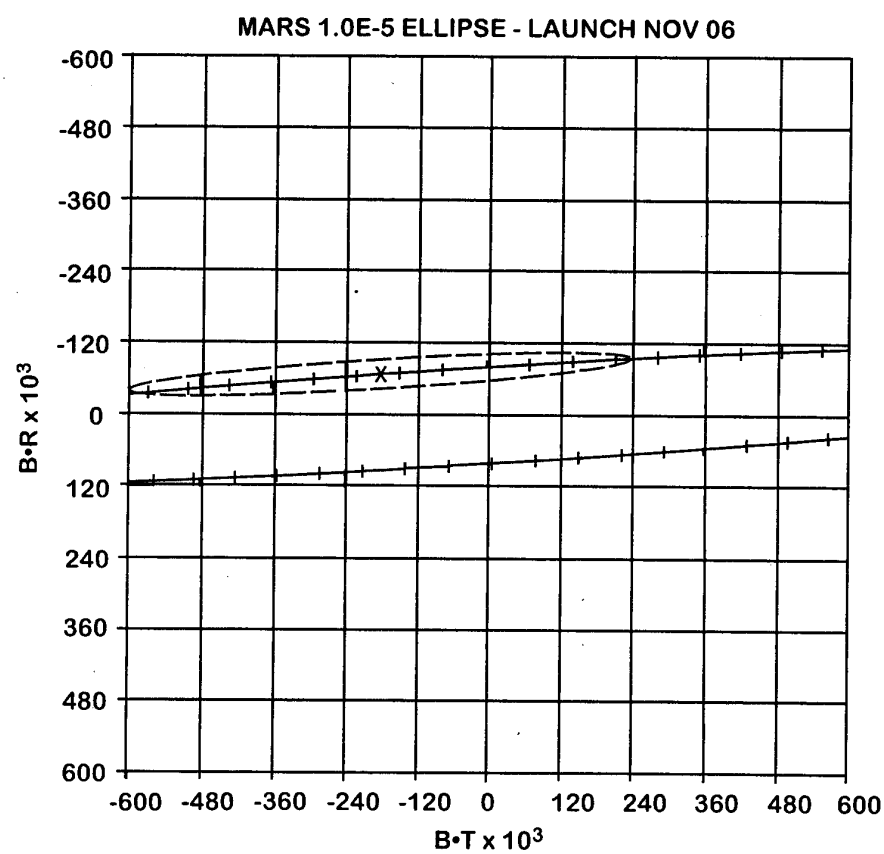


Figure 6.2
PQ Contour, Aim-point and (1-sigma) Dispersion Ellipse at Launch, 11/06/96, (Enlarged)

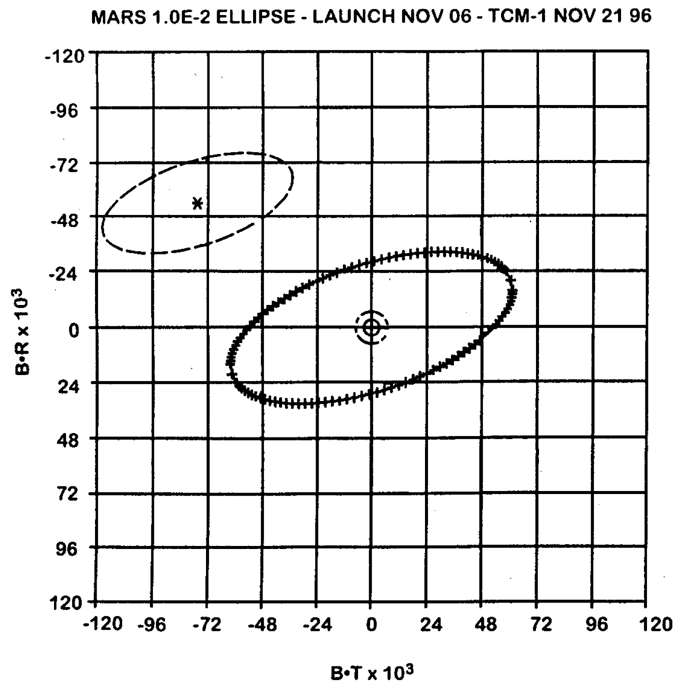


Figure 6.3
PQ Contour, Aim-point and (1-sigma)
Dispersion Ellipse at TCM-1, 11/21/96

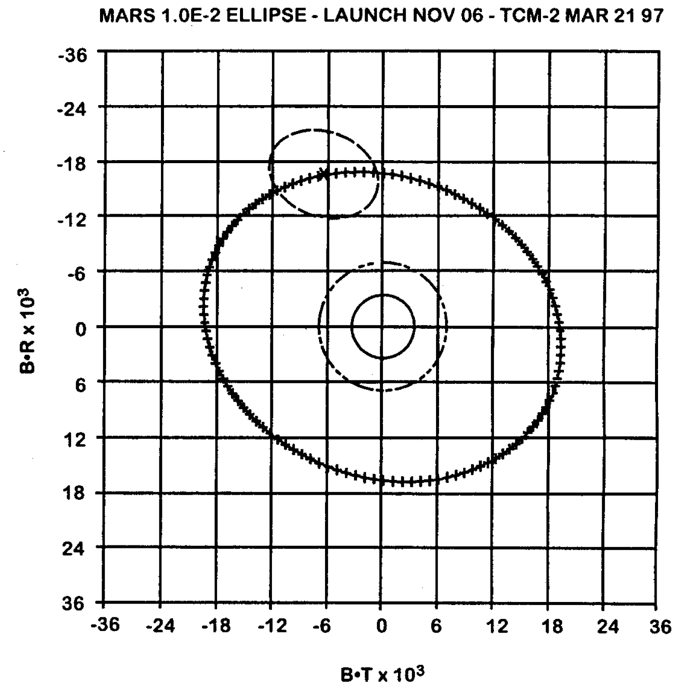


Figure 6.4
PQ Contour, Aim-point and (1-sigma)
Dispersion Ellipse at TCM-2, 3/21/97

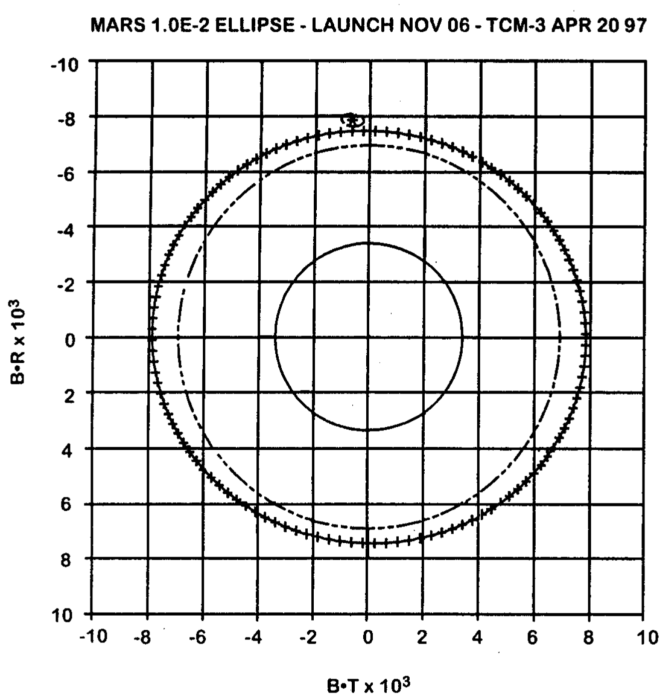


Figure 6.5
PQ Contour, Aim-point and (1-sigma)
Dispersion Ellipse at TCM-3, 4/20/97

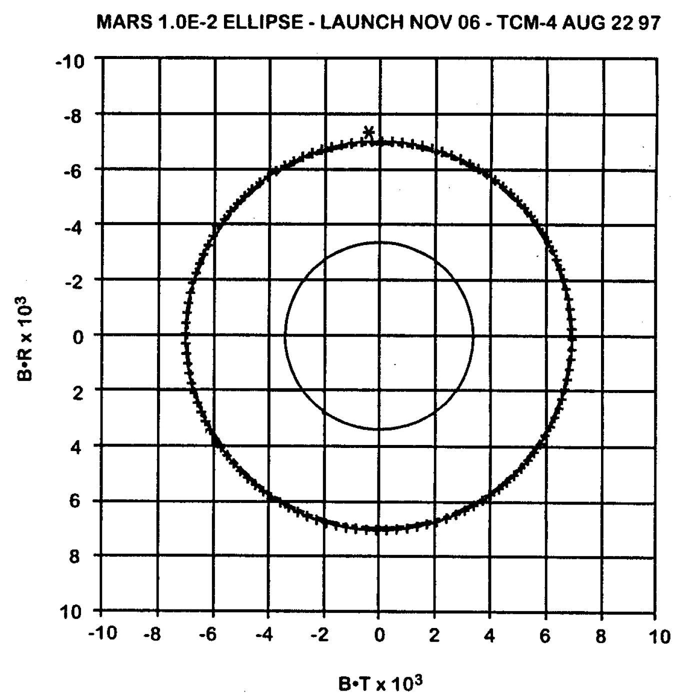


Figure 6.6
PQ Contour, Aim-point and (1-sigma)
Dispersion Ellipse at TCM-4, 08/22/97

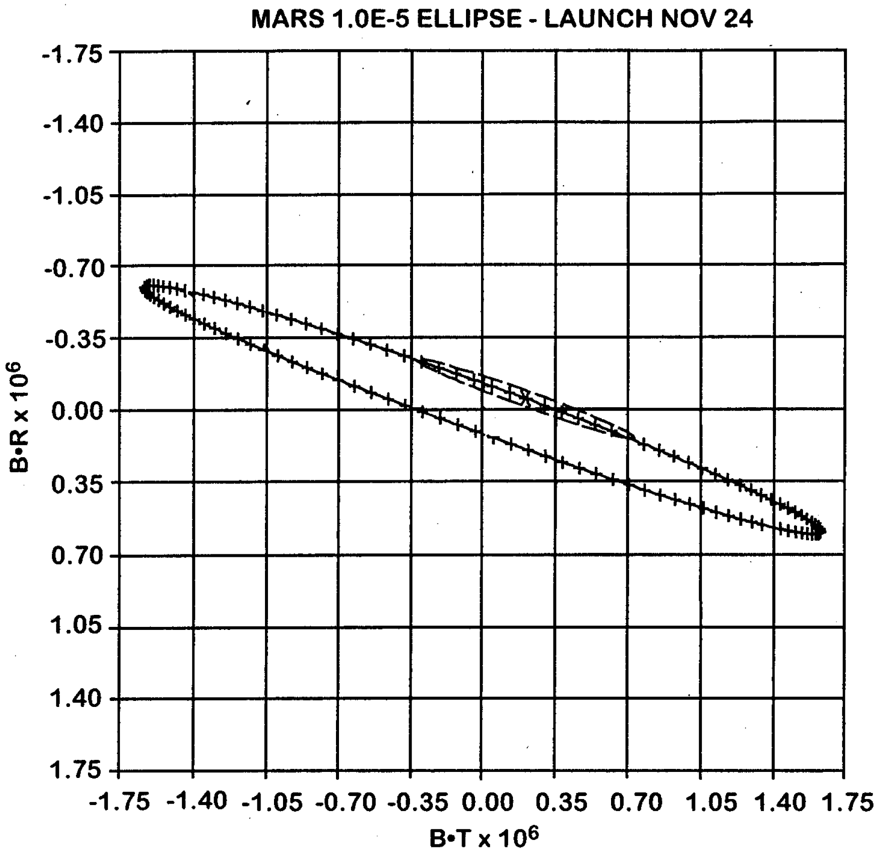


Figure 6.7

PQ Contour, Aim-point and (1-sigma) Dispersion Ellipse at Launch, 11/24/96

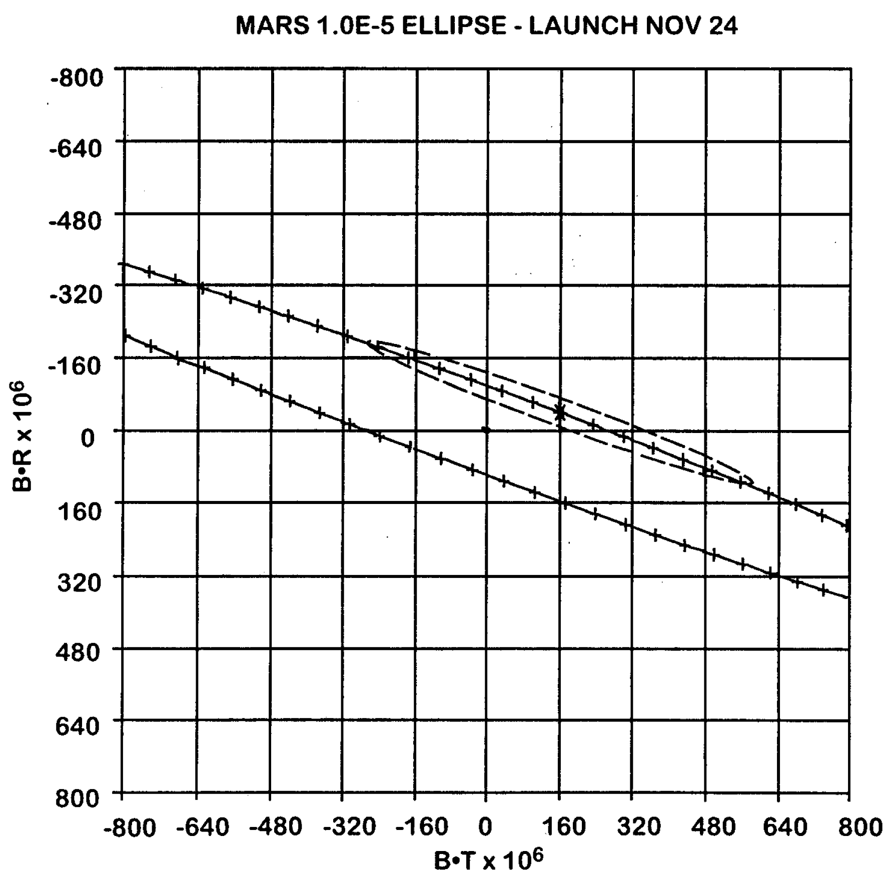


Figure 6.8

PQ Contour, Aim-point and (1-sigma) Dispersion Ellipse at Launch, 11/24/96, (Enlarged)

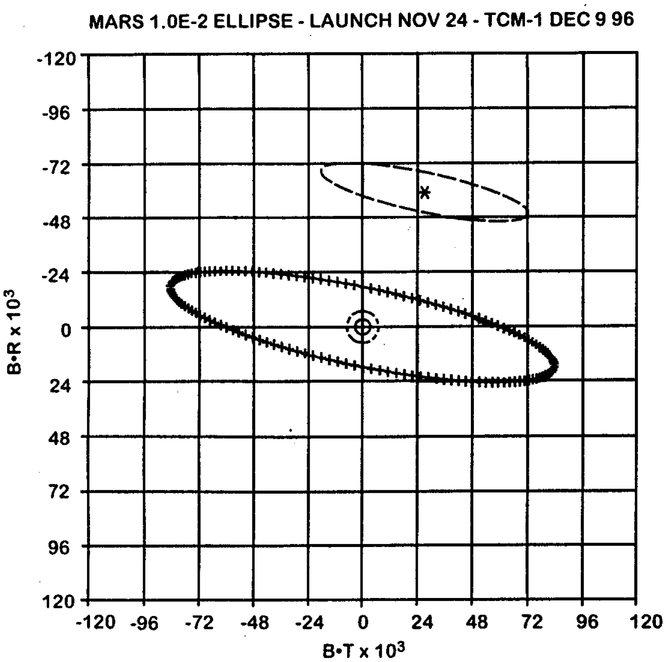


Figure 6.9
PQ Contour, Aim-point and (1-sigma) Dispersion Ellipse at TCM-1, 12/09/96

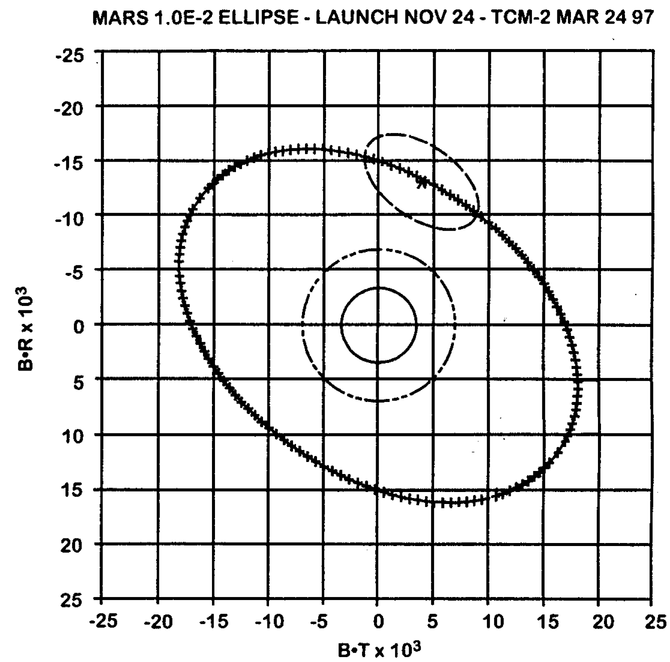


Figure 6.10
PQ Contour, Aim-point and (1-sigma) Dispersion Ellipse at TCM-2, 3/24/97

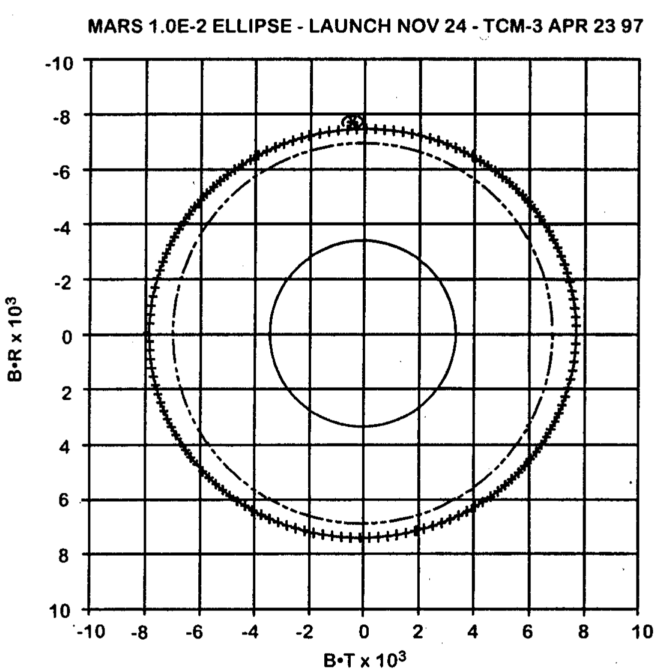


Figure 6.11
PQ Contour, Aim-point and (1-sigma) Dispersion Ellipse at TCM-3, 4/23/97

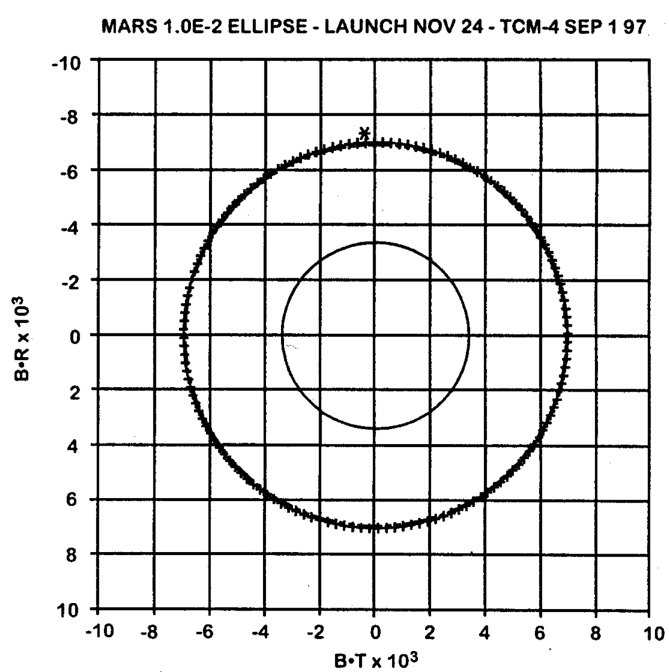


Figure 6.12
PQ Contour, Aim-point and (1-sigma) Dispersion Ellipse at TCM-4, 09/01/97

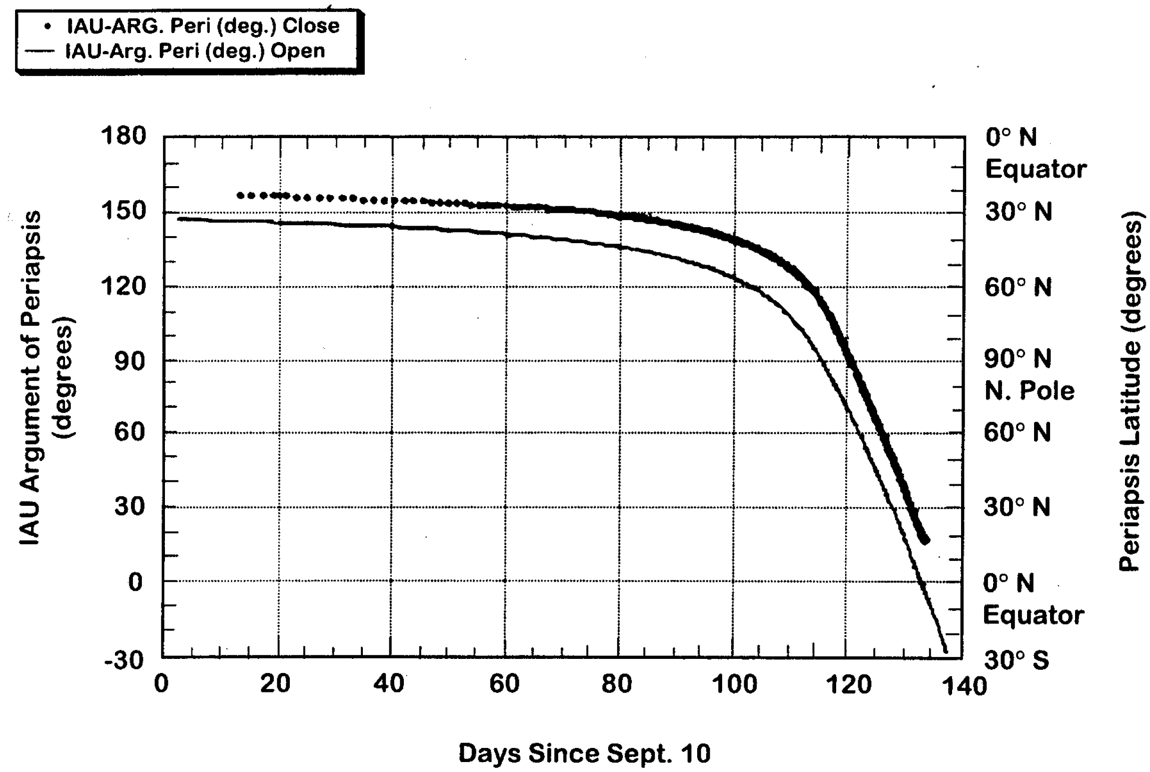


Figure 6.13
Argument of Periapsis vs Time During Aerobraking

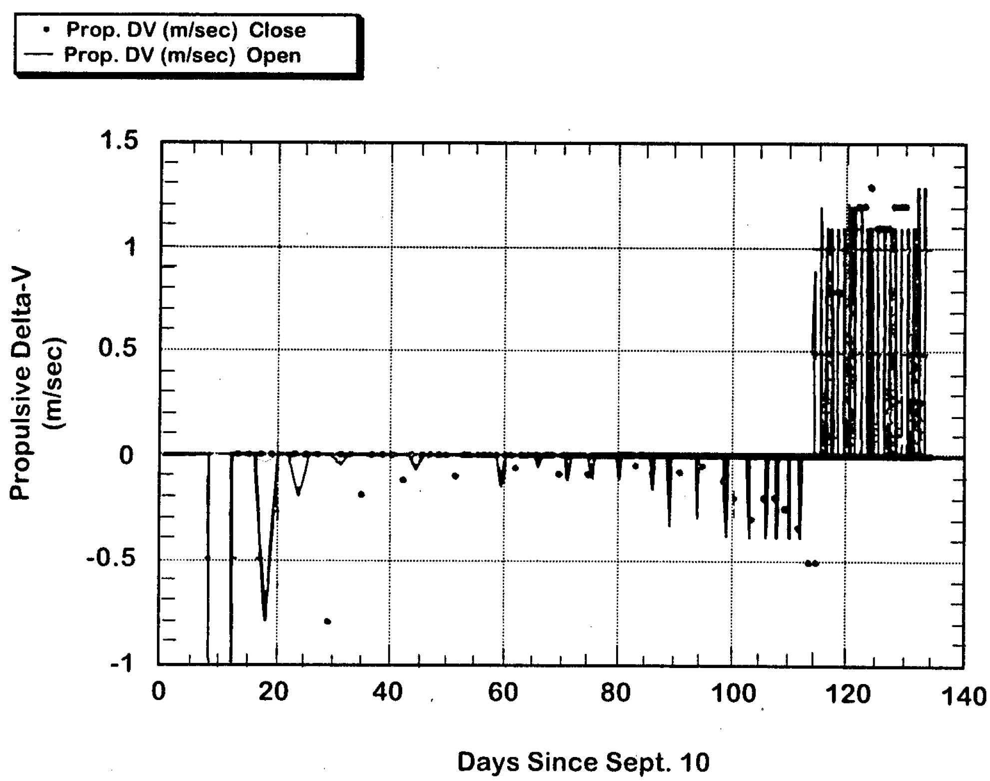


Figure 6.14
Propulsive Maneuvers During Aerobraking

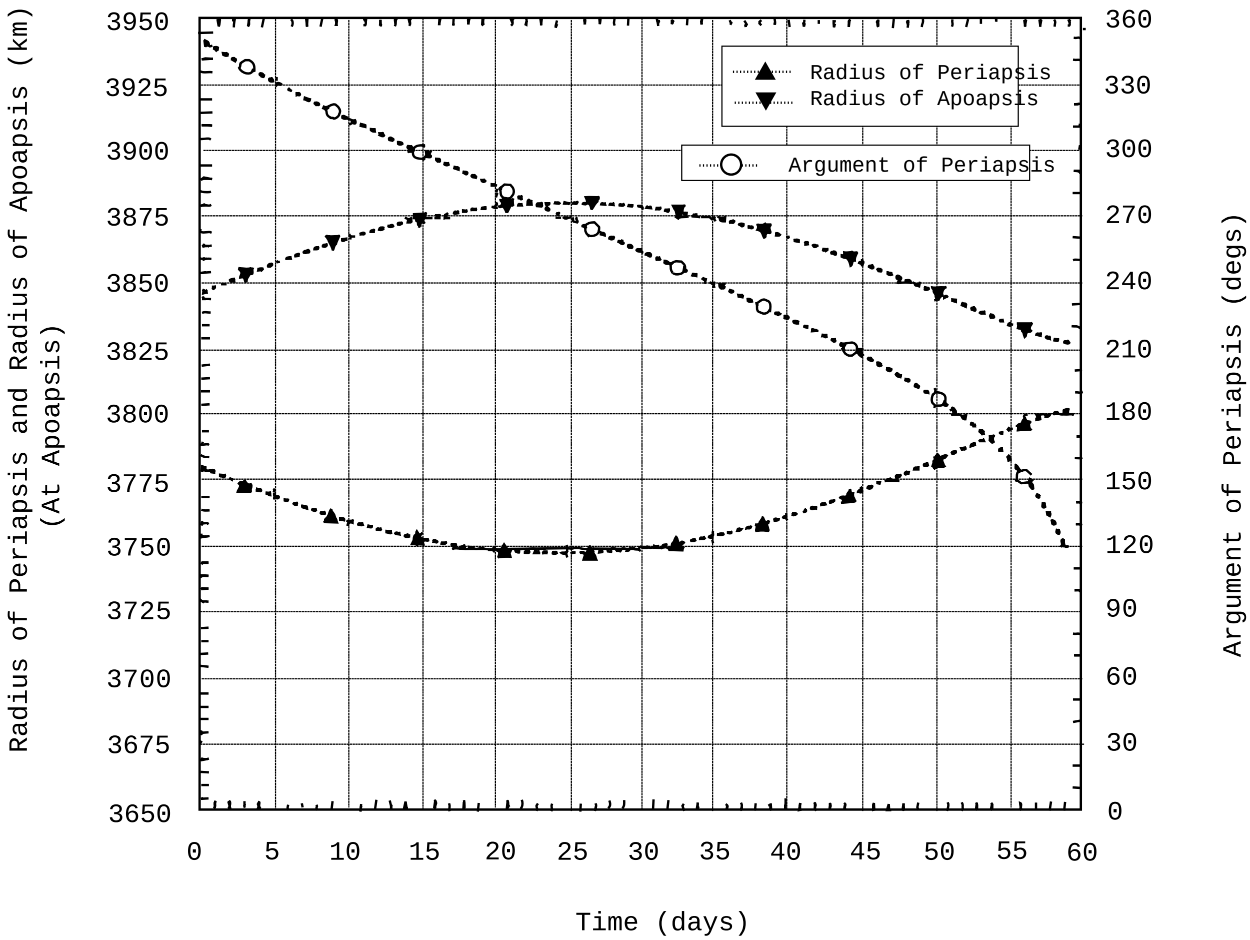


Figure 6.15
Periapsis and Apoapsis Radii and Argument of Periapsis
vs Time for Transition to Mapping Phase

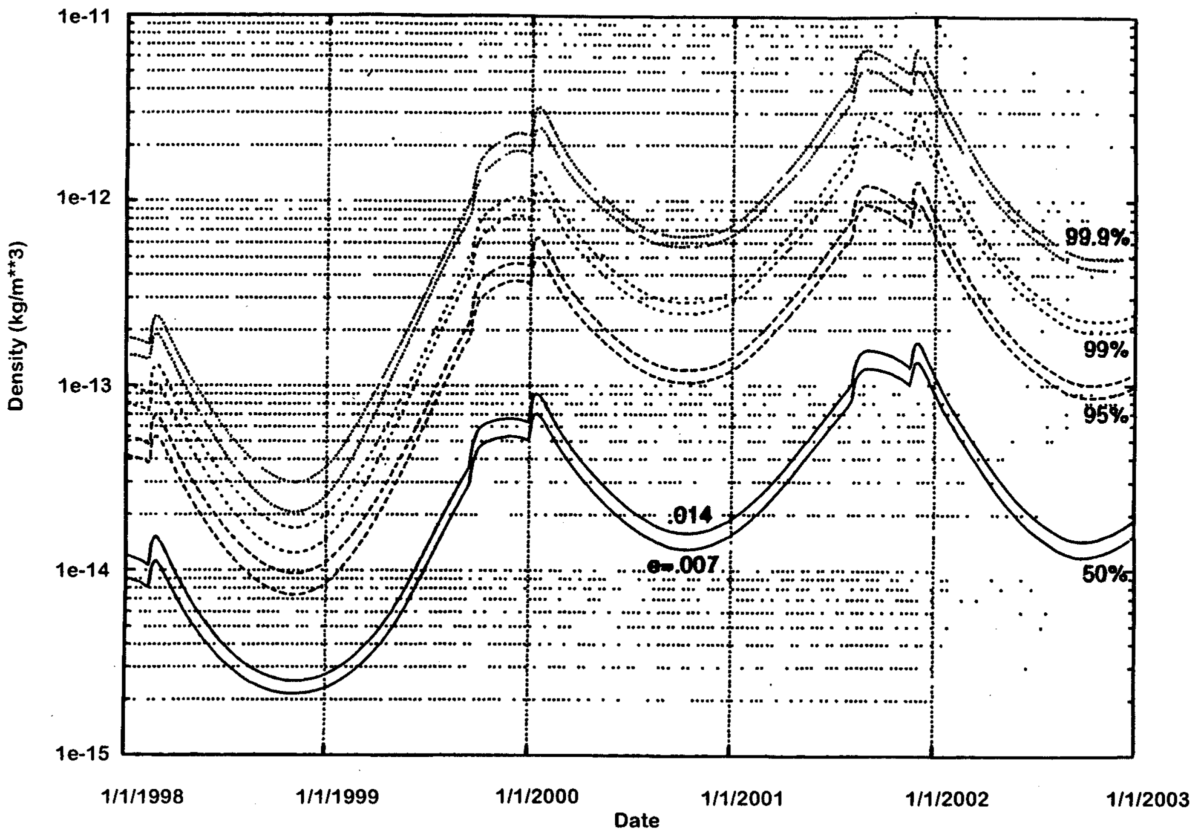


Figure 6.16
Orbit Averaged Atmospheric Density

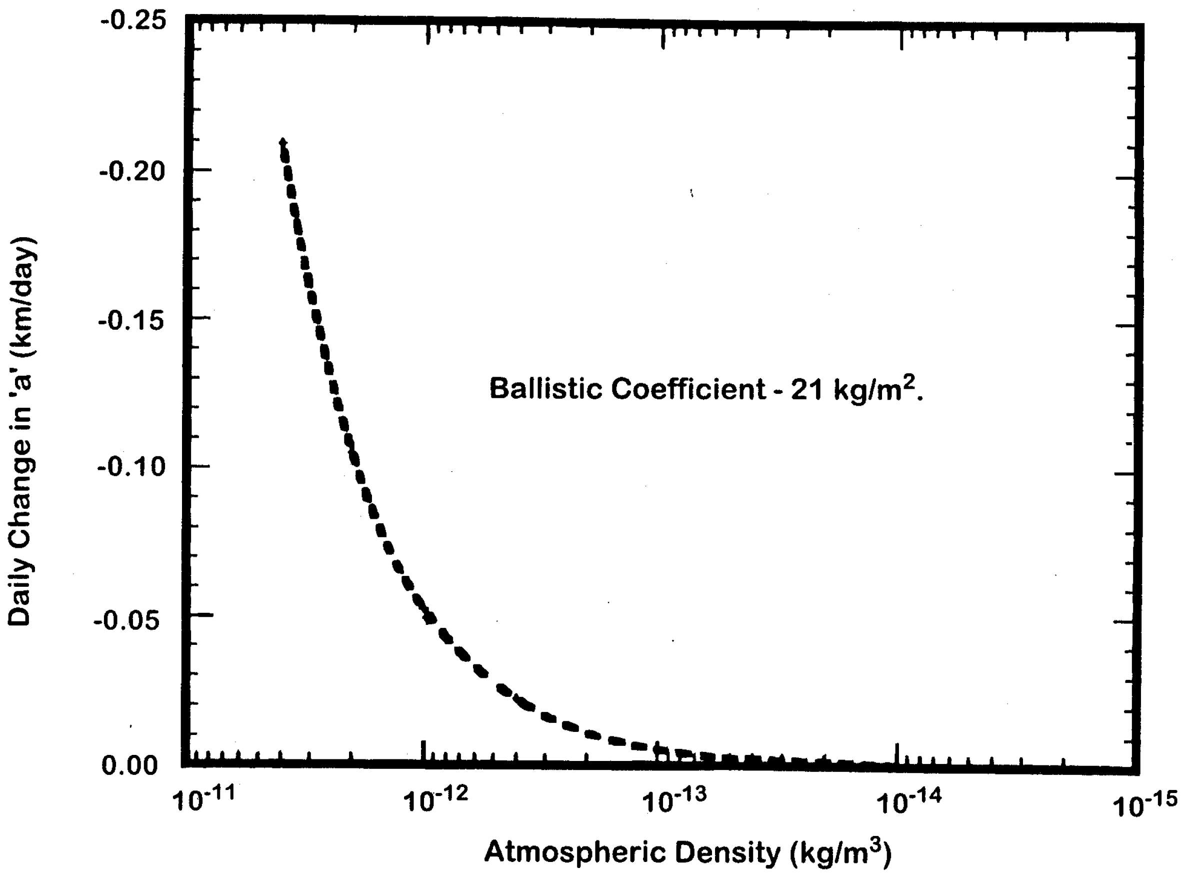


Figure 6.17
Daily Decay in Semi-major Axis due to Atmospheric Drag

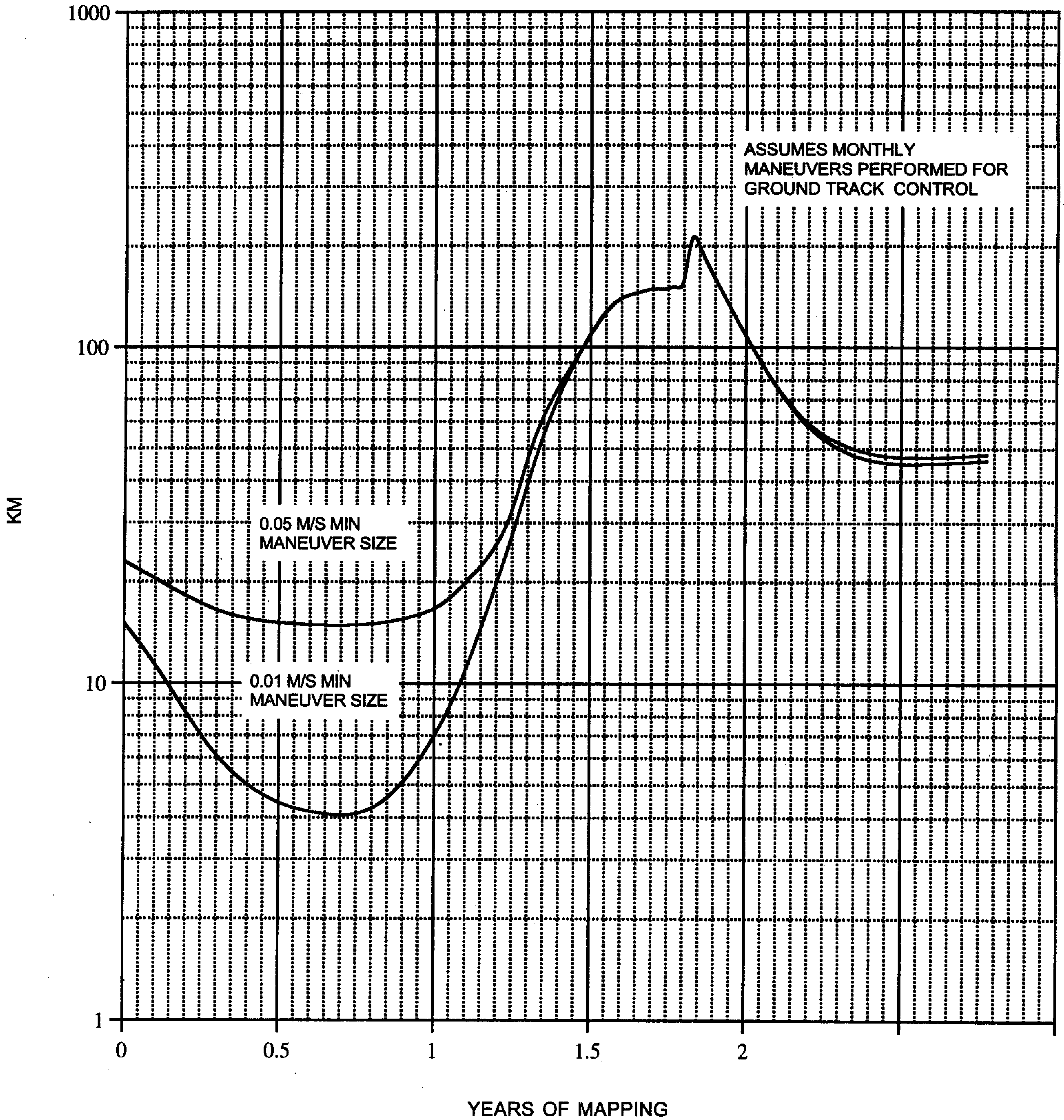


Figure 6.18
Preliminary 99% Ground Track Control vs Mapping Time

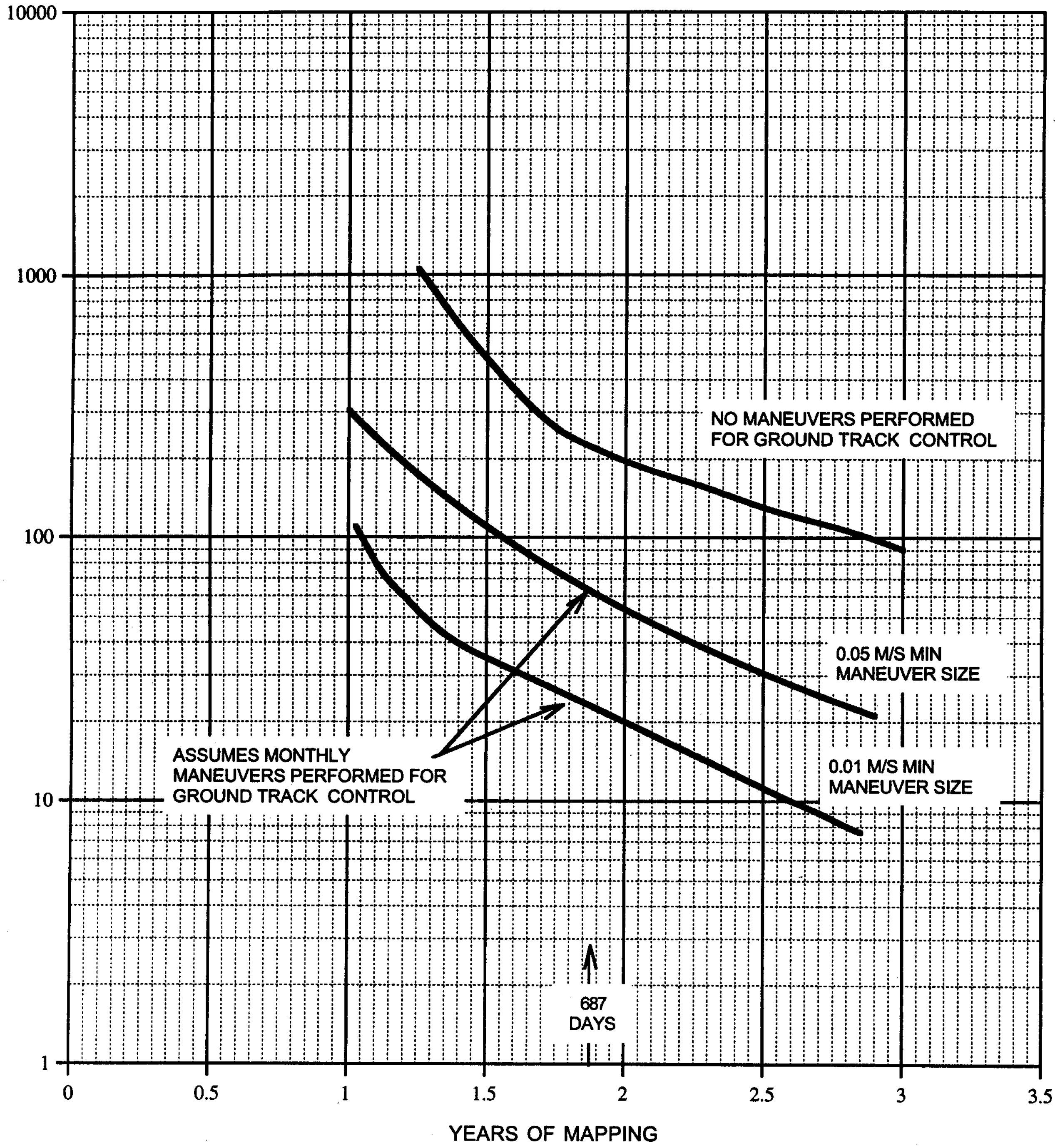


Figure 6.19
Preliminary Expected Number of Ground Track Separations Greater than 9 km vs Mapping Time

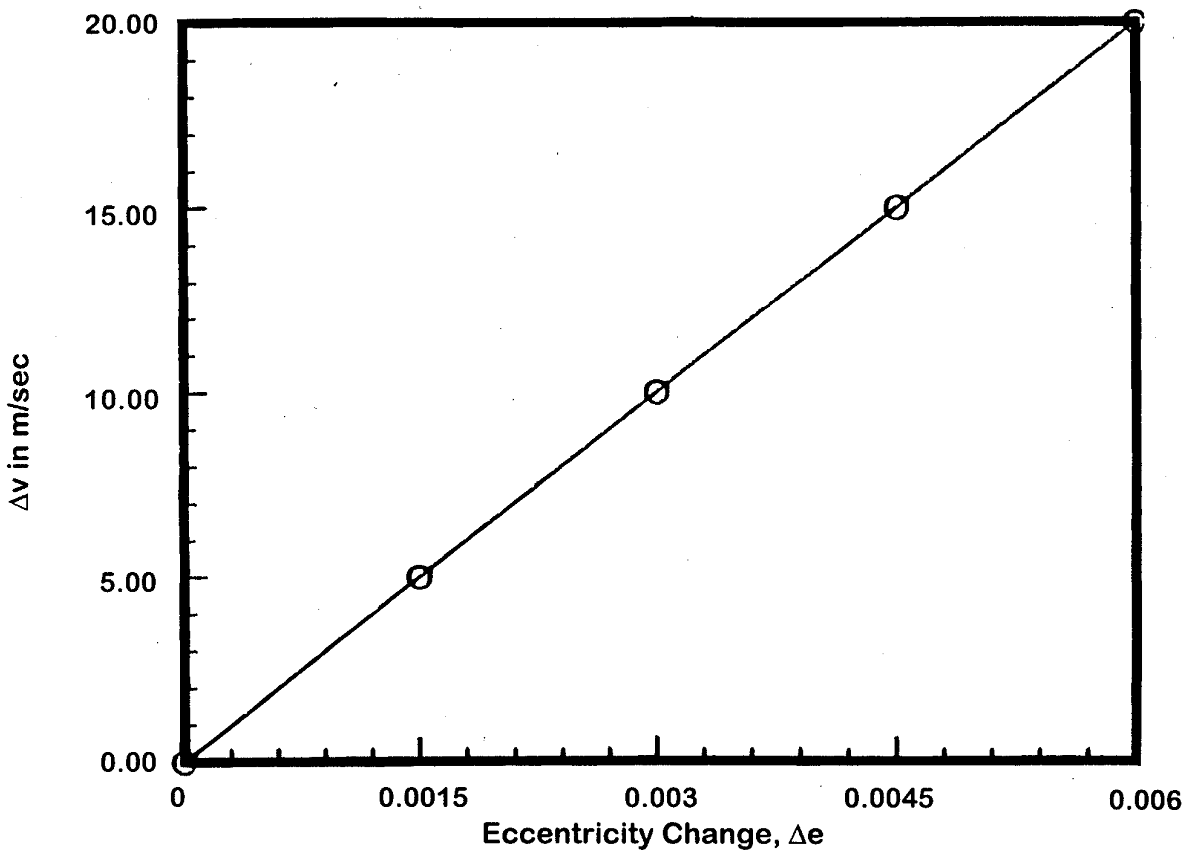


Figure 6.20
Delta-V to Change Eccentricity

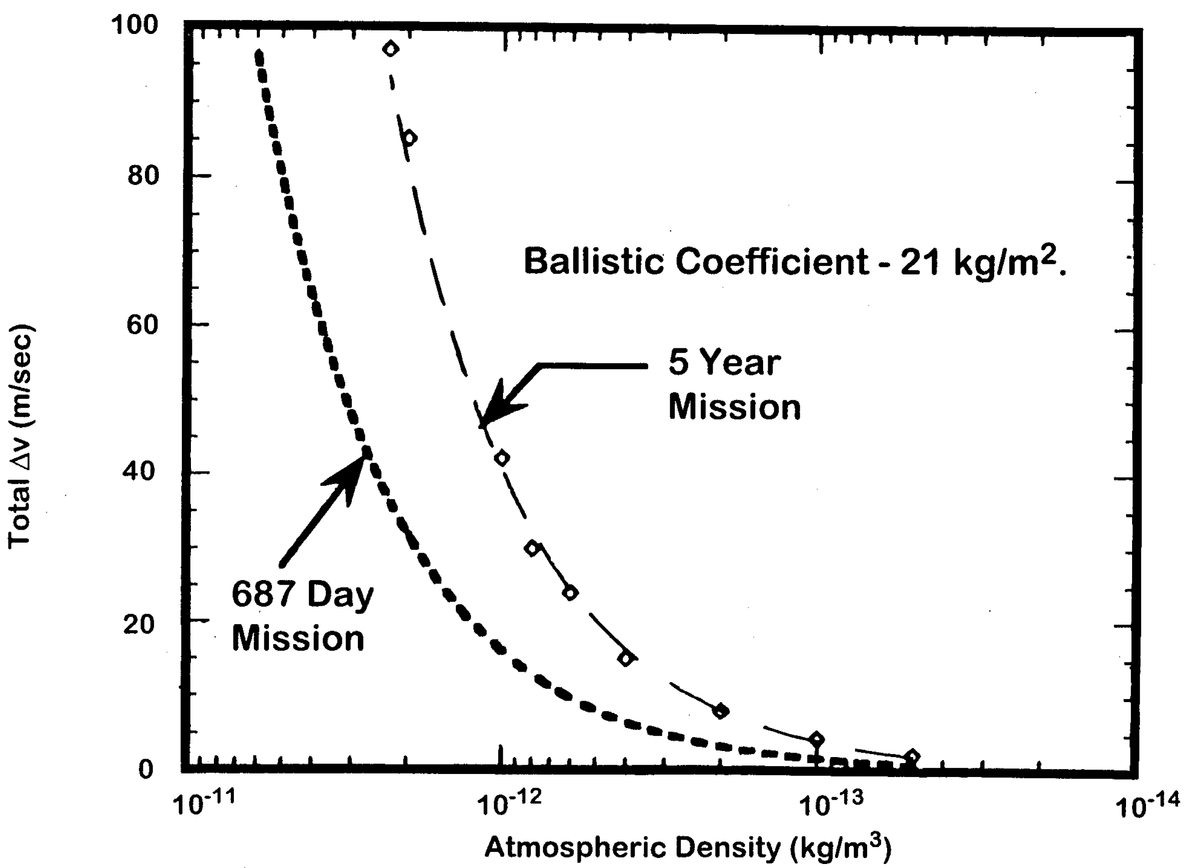


Figure 6.21
Total Delta-V for Drag Compensation

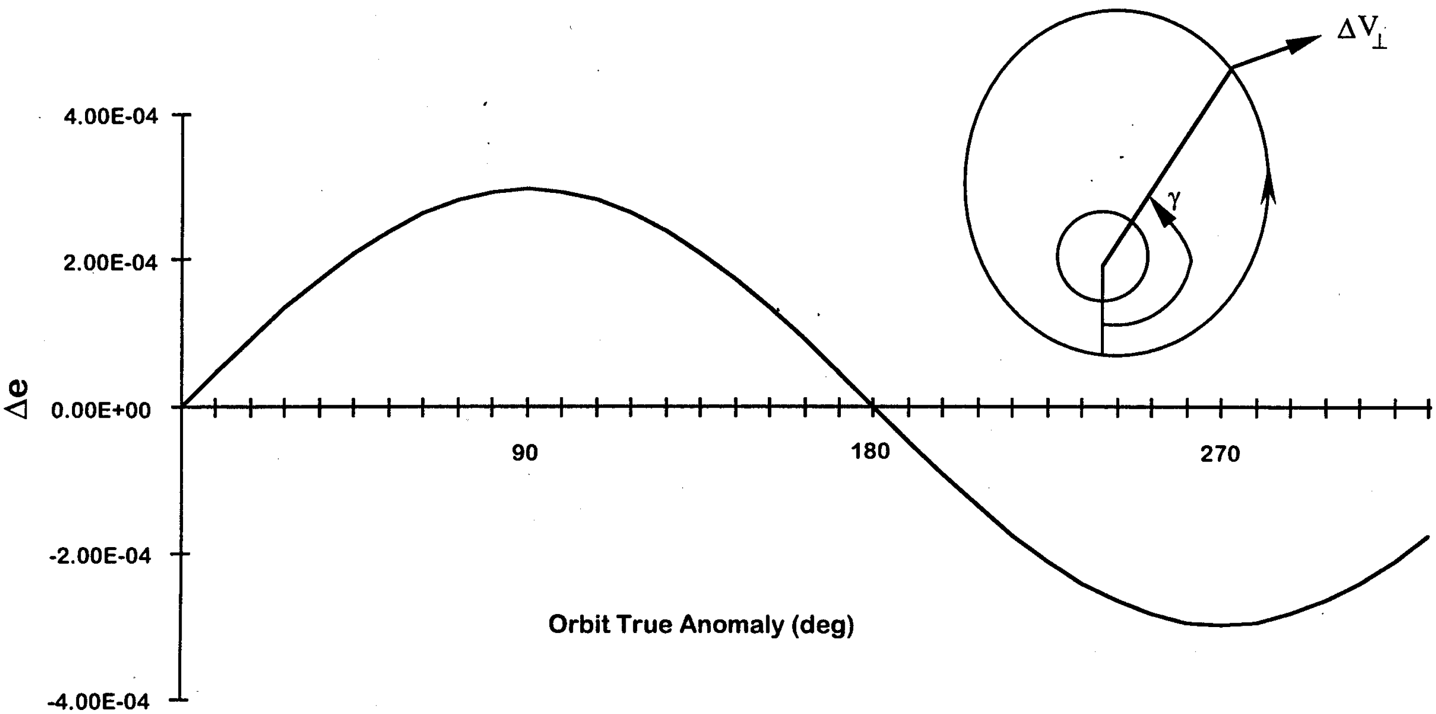


Figure 6.22
Change in Eccentricity for Perpendicular Velocity Correction

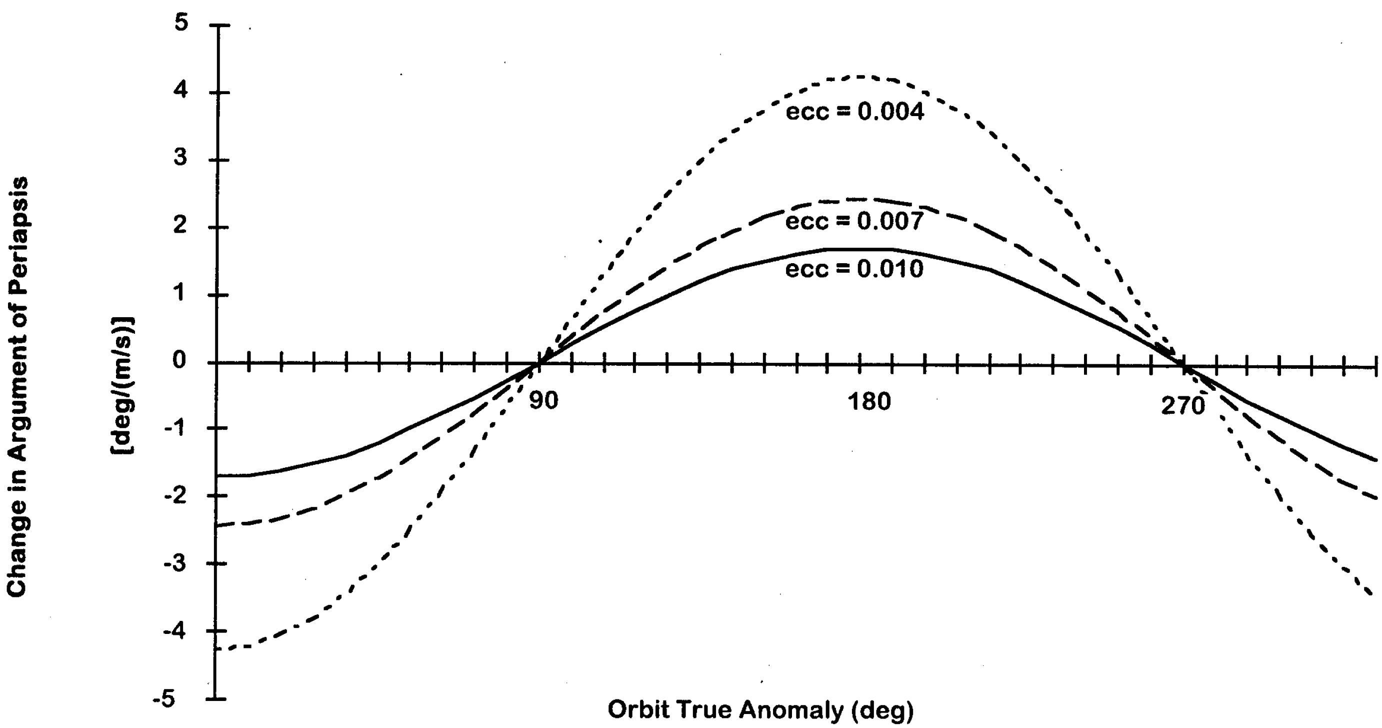


Figure 6.23
Change in Argument of Periapsis for Perpendicular Velocity Correction

7. NAVIGATION OPERATIONS PLANNING

7.1 NAVIGATION OPERATIONS PLAN: INJECTION TO TCM-1

Navigation requires two-way coherent Doppler and range data (also angular data) immediately after injection in order to a) assess the accuracy of the injection, b) provide the DSN with pointing and frequency predictions (P-files) and c) provide spacecraft ephemeris information to the SCT (SPK files). At injection plus 2-3 days, OD results shall be used to prepare the TCM-1 specification (MPF file) which is due at injection plus 5 days. Fig. 7-1 gives this daily work schedule and preliminary timeline.

7.2 NAVIGATION OPERATIONS PLAN FOR MOI

After the execution of TCM-4, at encounter minus 20 days, final preparations begin for the Mars orbit insertion (MOI) maneuver. This starts with the assessment of TCM-4 within 1-2 days of its execution. OD analysis shall continue for several more days with preliminary results due at the same day as the delivery of the MPDF from the SCT. Final OD results are due at E-13 days and the maneuver specification (the MPF) is due on E-12 days. Fig. 7.2 shows this preliminary timeline.

The unique aspect of this capture maneuver is that it will be executed in a “pitch-over” mode as opposed to the spacecraft being in an inertially fixed orientation. This will be the first time this type of propulsive maneuver is executed.

7.3 NAVIGATION OPERATIONS PLAN FOR AB - 1

After MOI, one orbit of tracking data shall be acquired for OD assessment of MOI and preparation for the first walkin maneuver called AB-1. The capture orbit periapsis has an altitude of 314. km and is at 32 deg latitude. AB-1 shall be executed at the fifth apoapsis (9 days or 4.5 orbits after MOI) and shall lower periapsis to 150. km. This shall be the first time that the spacecraft “senses” Mars’ atmosphere and this marks the beginning of the walkin phase.

A prelimimary navigation operations plan or work-schedule is given in Fig. 7.3 and Fig. 7.4.

7.4 NAVIGATION OPERATIONS PLAN FOR MAINPHASE AEROBRAKING

Fig. 7.5 gives an overview of navigation operations during the mainphase of aerobraking, an interval of 82 days (for the first launch). It shows six cases (based on orbital period) that were analyzed for Tp prediction accuracy.For the longer period orbits (i. e. greater than six hours), only one orbit plus several hours of post-periapsis tracking data are required for the OD.For these four cases, only one Tp prediction within the 225 s accuracy requirement is possible.The dominant factor is the level of orbit-to-orbit variation or uncertainty in the atmospheric density . We used a 70% density variation which was determined from the Mars atmospheric density workshop and guidelines provided by the project.

The next two figures show the OD strategy for the case when the orbital period is three hours. Data acquisition begins at To and continues for two orbits plus 1.5 hours after P2 (note that no data is acquired within one-half hour of periapsis). The timeline shows that approximately 6.25 hours is necessary from P2 until the Tp predictions have been received by the spacecraft. In addition, because of the communication blackout prior to periapsis, due to eclipse (or occultation) and preparation for the drag pass (i. e. spacecraft turns to the correct attitude and some allocation for margin), the uplink must be completed between 46 minutes (maximum) to 25 minutes (minimum) prior to periapsis.

Currently only two Tp predictions (i. e. P5 and P6) , satisfying the accuracy requirement, can be generated per analysis (see Table 5.12). The prediction for P4 easily satisfies the requirement but, according to the current timeline, is available too late to be transmitted to the spacecraft. At the other extreme, the Tp prediction for P7 is too inaccurate to be useful (under the 70% density variation assumption). In order for the P4 prediction to be useful for operations, the timeline would have to be reduced by approximately one hour. A review was performed with this objective in mind. While some savings were evident, these cannot be committed to until the operations software undergo realistic simulations and tests.

The primary penalty for inaccurate Tp predictions is a small amount of extra propellent consumption for attitude control.Thus occasionally exceeding the requirement can be tolerated (Ref. 5.3). Furthermore, this reference also gives an indication of how much the 225. s requirement can be relaxed for orbital periods from six to two hours. These are given in Table 5.12.

NAVIGATION OPERATIONS WEEKLY TIMELINE
INJECTION THROUGH TCM-1: PLAN, IMPLEMENTATION AND ASSESSMENT

DATE (PST) NOV,1996 WRT LAUNCH	TUESDAY 5 -1	WEDNESDAY 6 0	THURSDAY 7 1	FRIDAY 8 2	SATURDAY 9 3	SUNDAY 10 4	MONDAY 11 5
INPUTS (PST)		I (0958)					
ODF, CAL		1300,SPEC	0800, SPEC	0800	0800	0800	0800
AMD		TBD	TBD				
MPDF			0800		0800		
PROCESS							
OD		X	X	X	X	X	X
MNVR			X	X			X
PREDICTS		X	X	X		X	
MODEL (AMD)		X	X	X	X		
OUTPUTS (PST)							
P-FILE		2000	1200	1200		1700	
SPK			1200			1700	
GIN/SALINFO			1200			1700	
MPF							1700
MIF/SASF							
ASSESSMENT		1800	1800				

INJECTION = TECO = 11/06/96, 17:58 ET (SCET) = 11/06/96, 9:58 AM PST (ERT)
TCM-1 OCCURS ON 11/21/96

FIG. 7.1 PRELIMINARY NAVIGATION OPERATIONS TIMELINE : INJECTION THROUGH TCM-1.

NAVIGATION OPERATIONS WEEKLY TIMELINE
MOI PLAN, IMPLEMENTATION AND ASSESSMENT

DATE (PDT) AUG,1997 WRT MOI	MONDAY 18 -24	TUESDAY 19 -23	WEDNESDAY 20 -22	THURSDAY 21 -21	FRIDAY 22 -20	SATURDAY 23 -19	SUNDAY 24 -18
INPUTS (PDT)							
ODF, CAL	0800	0800	0800	0800	0800	0800	0800
AMD							
MPDF							
PROCESS					TCM-4		
OD			X	X	X	X	X
MNVR							
PREDICTS			X			X	
MODEL							
OUTPUTS (PDT)							
P-FILE						1700	
SPK						1700	
GIN/SALINFO						1700	
MPF							
MIF/SASF							
ASSESSMENT					1800	1800	

ENCOUNTER (UNBRAKED PERIAPSIS) = 9/11/97, 01:28 ET (SCET) = 9/10/97, 6:41 PM PDT (ERT)

MOI BURN DURATION = 25 MIN (CENTERED ON PERIAPSIS), ΔV = 976. M/S (BI-PROP, 596. N)

FIG 7.2 PRELIMINARY NAVIGATION OPERATIONS PLAN FOR MARS ORBIT INSERTION.

NAVIGATION OPERATIONS WEEKLY TIMELINE
MOI PLAN, IMPLEMENTATION AND ASSESSMENT (CONT.)

DATE (PDT) AUG,1997 WRT MOI	MONDAY 25 -17	TUESDAY 26 -16	WEDNESDAY 27 -15	THURSDAY 28 -14	FRIDAY 29 -13	SATURDAY 30 -12	SUNDAY 31 -11
INPUTS (PDT) ODF, CAL AMD MPDF	 0800 	 0800 	 0800 0800	 0800 	 0800 	 0800 	
PROCESS OD MNVR PREDICTS MODEL	 X	 X	 X X	 X	 X X	 X X	
OUTPUTS (PDT) P-FILE SPK GIN/SALINFO MPF MIF/SASF ASSESSMENT			 1200 1200 1200		 1200 1200 1200	 1200	

ENCOUNTER (UNBRAKED PERIAPSIS) = 9/11/97, 0128 ET (SCET) = 9/10/97, 6:41 PM PDT (ERT)
MOI BURN DURATION = 25 MIN (CENTERED ON PERIAPSIS), ΔV = 976. M/S (BI-PROP, 596. N)

FIG. 7.2 PRELIMINARY NAVIGATION OPERATIONS PLAN FOR MOI (CONT.) .

NAVIGATION PREPARATION FOR AB-1 (OVERVIEW)

TIMELINE, TASKS AND INFORMATION EXCHANGE (VIA PDB AND OSCAR)

DAYS	0	1	2	3	4	5	6	7	8	9	10	11	12
PERIAPSIS	P1		P2		P3		P4		P5		P6		P7
APOAPSIS		A1		A2		A3		A4		A5		A6	
EVENTS	MOI		314. KM							AB-1, 150. KM			
W-HOURS	8	...										8	
TASK	TRK DATA ACQ AND OD		OD	MVR DSN	MVR IMP	SEQ STL REV	STL APRV RAD		TRK DATA ACQ EVAL AB-1 PREP AB-2			OD	
PRODUCTS, FILES	MPDF AMD P-FILE ODF,CAL		SPK	MPF SPK	MIF SASF P-FILE	SEQ REV	REV AP MEET GCMD				MPDF AMD P-FILE ODF,CAL		

TRK DATA CONTINUOUS WITH ROUTINE AND SOME SPECIAL DELIVERIES

DURATION 9 DAYS FROM P1 TO A5

FIG. 7.3 OVERVIEW OF NAVIGATION OPERATIONS FOR THE FIRST WALKIN MANEUVER.

NAVIGATION OPERATIONS WEEKLY TIMELINE
AB-1 PLAN, IMPLEMENTATION AND ASSESSMENT

DATE (PDT) SEPT,1997 WRT MOI	MONDAY 8 -2	TUESDAY 9 -1	WEDNESDAY 10 0 (MOI)	THURSDAY 11 1	FRIDAY 12 2	SATURDAY 13 3	SUNDAY 14 4
INPUTS (PDT) ODF, CAL AMD MPDF	 0800 	 0800 0800?	 0800, SPEC 	 0800, SPEC 0800 0800	 0800, SPEC 0800 	 0800 	 0800
PROCESS OD MNVR PREDICTS MODEL	 X 	 X 	P1 (1841) X X 	 X 	P2 X X X	 X X 	P3 X
OUTPUTS (PDT) P-FILE SPK GIN/SALINFO MPF MIF/SASF			 2400 	 1800 1800 1800 		 1700 1700 1700 (NIGHT IS MARGIN)	 1700

ENCOUNTER (UNBRAKED PERIAPSIS) = 9/11/97, 01:28 ET (SCET) = 9/10/97, 6:41 PM PDT (ERT) FOR 11/6/96 L.
MOI BURN DURATION = 25 MIN (CENTERED ON PERIAPSIS), ΔV = 976. M/S (BI-PROP, 596. N)

FIG 7.4 PRELIMINARY NAVIGATION PLANNING FOR THE FIRST WALKIN MANEUVER.

NAVIGATION OPERATIONS WEEKLY TIMELINE
AB-1 PLAN, IMPLEMENTATION AND ASSESSMENT (CONT.)

DATE (PDT) SEPT,1997 WRT MOI	MONDAY 15 5	TUESDAY 16 6	WEDNESDAY 17 7	THURSDAY 18 8	FRIDAY 19 9 (AB-1)	SATURDAY 20 10	SUNDAY 21 11
INPUTS(PDT) ODF, CAL AMD MPDF	 0800	 0800	 0800	 0800	 0800,SPEC 0800	 0800, SPEC 0800 0800 ?	 0800, SPEC 0800
PROCESS OD MNVR PREDICTS MODEL	 X	P4 X	 X	P5 X X	A5 : 1841 X X	P6 X X X	 X X X X
OUTPUTS(PDT) P-FILE SPK GIN/SALINFO MPF MIF/SASF					 2400	 2400	 1700 1700 1700 OFF SHELF

AB-1 EXECUTION (A5) = 9/20/97, 0128 ET (SCET) = 9/19/97 , 6:41 PM PDT (ERT) ; ΔV = 6.53 M/S
AB-2 EXECUTION (A9) : 8 DAYS (OR FOUR ORBITS) FROM AB-1 TO AB-2 (A5 TO A9)

FIG 7.4 PRELIMINARY NAVIGATION PLANNING FOR THE FIRST WALKIN MANEUVER (CONT.).

NAVIGATION MAINPHASE AEROBRAKING OPERATIONS OVERVIEW

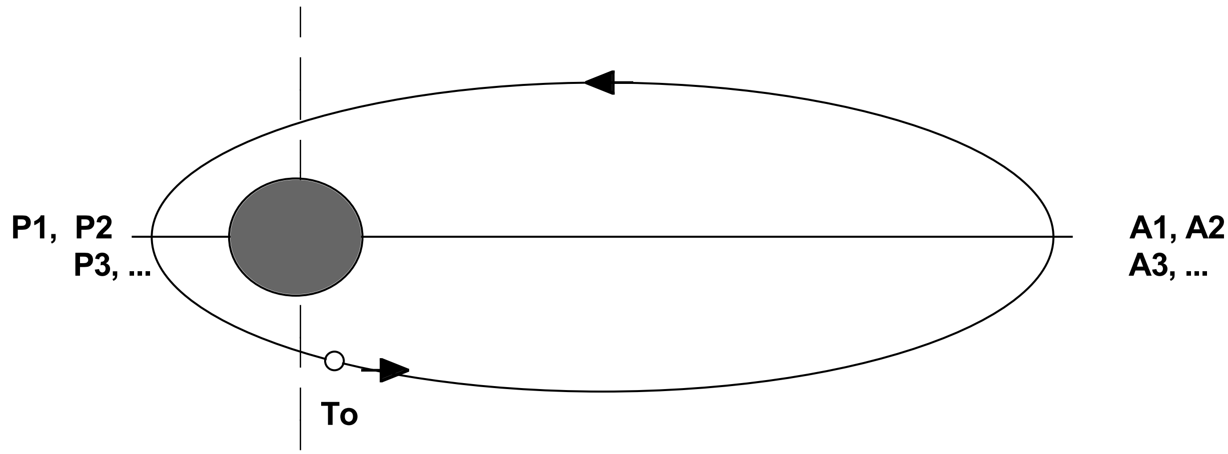
MOI + / PERIOD (HRS)	DATA * ACQ (ORBITS)	Tp PRE-DICTION NO. ; Pi	NAV ANALYSIS (HOURS)	FILE DELIVERY SCHEDULE (EVERY N HOURS) ODF	OPTG / SPK
+31 DAYS 40.	1	1 ; P2	6	24	40
+55 DAYS 24.	1	1 ; P2	5	24	24
+81 DAYS 10.	1	1 ; P2	4	10	10
+94 DAYS 6.0	1	1 ; P3	3	6	6
+107 DAYS 3.0	2	2 ; P5, P6	3	6	6
+110 DAYS 2.42	2	3 ; P6, P7, P8	3	7.2	7.2

* NAV REQUIRES 4 TO 1 HRS OF POST-PERIAPSIS TRACKING DATA.

- FILE DELIVERY SCHEDULE IS DETERMINED BY THE NUMBER OF Tp PREDICTIONS PER NAV ANALYSIS
- TIME INTERVAL FROM P = 6 HRS TO P = 2.42 HRS (START OF WALKOUT) : 18 DAYS OR 115 ORBITS

FIG 7.5 OVERVIEW OF NAVIGATION OPERATIONS DURING THE MAINPHASE OF AEROBRAKING

AEROBRAKING ORBIT DETERMINATION STRATEGY




```
                                       D/L                                    U/L
TIMELINE          I------------I---------------------I*I-------------------------I-----------------I*I   ....   I--------I
OVERVIEW, HRS     P  ± 0.5        1.0                   3.0                  1.0                   0.75   P
( APPROX )        NO          NAV DATA              NAV                  GROUND                DRAG
                  DATA        ACQUISITION           ANALYSIS             PREP                  ENTRY
```

TOTAL DURATION (HRS) = 6.25 + 0.75

PURPOSE : PROVIDE PREDICTED Tp AND Rp FOR SPACECRAFT ENTRY INTO THE DRAG PASS OR PERIAPSIS .
To REFERS TO THE START OF THE TRACKING DATA ACQUISITION ; PERIAPSIS 1 AND 2 (P1, P2) OCCUR DURING THIS DATA ACQUISITION (PERIOD = 3 HRS).

FIG 7.6 OVERVIEW OF NAVIGATION ORBIT DETERMINATION STRATEGY DURING AEROBRAKING.

AB ORBIT DETERMINATION TIMELINE (P= 3.0 HRS)

EVENT	TIME DURATION (HMS)	TIME ACCUM'D (HRS)
EPOCH, To (12/29/97, 00:59:45 ET)	---	0.0
P1, P2	---	2.5, 5.5
END DOPPLER DATA ACQUISITION	---	7.0
DOWNLINK (OWLT) AND TRANSFER TO RMDCT	00:18:36	7.31
RMDCT ANALYSIS	00:10:00	7.48
TRANSFER DATA TO DSN NODE	00:01:00	7.49
TRANSFER DATA TO NAV COMPUTER	00:05:00	7.58
P3	---	8.5
NAV ANALYSIS	03:00:00	10.58
P4	---	11.5
GROUND PREPARATION	01:00:00	11.58
UPLINK TO SPACECRAFT (OWLT)	00:17:36	11.86
P5 ---	---	14.5

• • • U/L REACHES SPACECRAFT APPROX 2.6 HRS BEFORE P5

AFTER THE Tp (P5 AND P6) DELIVERY, PREPARE THE NEXT NAV ANALYSIS WHICH SHALL PROVIDE THE Tp (P7 AND P8) PREDICTIONS

NOTES

To = EPOCH OF START OF NAV DATA ACQUISITION (2 ORBITS AND 1 HR)

ONE WAY LIGHT TIME (OWLT) = 17 MIN 36 S

PERIOD CHANGE PER ORBIT (APPROX) = 1 MIN 40 S

OCCULTATION DURATION: 21.0 MIN ECLIPSE DURATION: 35.5 MIN

SPACECRAFT EMERGES FROM OCCULTATION: P2 - 1 MIN, 10 S

FIG 7.7 NAVIGATION OPERATIONS TIMELINE DURING AEROBRAKING (P = 3 HOURS)

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9. APPENDIXES

9.1 INJECTION INITIAL CONDITIONS AND COVARIANCE

9.1-A Old First Launch Date and Covariance

Three interplanetary phase trajectories were provided by Mission Design (first, middle and last launch dates). Orbital and tracking data information at TECO (11/05/96, 18:26:17 ET, SCET) for the first launch date are given in the following table.

TABLE 9.1-1A ORBITAL INFORMATION AT TECO

Altitude (km)	221.0
Longitude (deg)	75.4
Latitude (deg)	-28.7
First DSN Acquisition	DSS-45 at TIP + 40 min (approx)
(Two-way Coh. Doppler)	(LGA, +X axis, is Sun pointed)

The injection uncertainties at the TIP (first launch) are given in Table 9.1-2A. They are referenced to an upper stage spin of 70 rpm, a time constant of 30 s and a probability of command shut-down of the second stage (PCS) of 99.7%.

TABLE 9.1-2A MGS INJECTION COVARIANCE

```
        INJECTION COVARIANCE
        MANDAT='21-NOV-1996 18:12:59.4327',
        INJDAT='06-NOV-1996 18:12:59.4327',
        CODE='TNR',
        UNIT='FTFPS'
        COV=
.41573276E10, -.18453819E7,  .16286126E9,  .49177478E5,  .14790685E4,
                                                        -.43901738E7,
              .100781120E7, -.10970500E6, -.58141010E1, -.45155799E4,
                                                         .18346173E4,
                             .28140143E8, -.17442916E5,  .9409285E2,
                                                        -.16280626E6,
                                           .15134506E3, -.53686192E2,
                                                        -.41597736E3,
                                                         .47788523E4,
                                                        -.59675867E1,

                                                         .93694786E4,
;
```

NOTES: 1. The above covariance corresponds to the Nov. 6, 1996 LAUNCH DATE in the TNR or NASA coordinate system in FT, FT PER SEC units.
This is what is received from McDonnell Douglas Aerospace.

2. NASA COORDINATE SYSTEM DEFINITION:
The origin is at the vehicle's nominal present position. The positive x-axis is parallel to the projection of the nominal inertial velocity onto a plane perpendicular to the nominal radius vector. The z-axis is positive away from the earth along the nominal radius vector. The y-axis completes the right-handed orthogonal system.

3. The above covariance corresponds to the THIRD STAGE NOMINAL SPIN RATE OF 70 RPM AND NUTATION TIME CONSTANT OF 30 SEC.

9.1-B Updated First Launch Date and Covariance

Three interplanetary phase trajectories were provided by Mission Design (first, middle and last launch dates). Orbital and tracking data information at TECO (11/06/96, 17:57:46 ET, SCET) for the first launch date are given in the following table.

TABLE 9.1-1B ORBITAL INFORMATION AT TECO

Altitude (km)	221.0
(East) Longitude (deg)	81.3
Latitude (deg)	-28.5
First DSN Acquisition	DSS-45 at TIP + 40 min (approx)
(Two-way Coh. Doppler)	(LGA, +X axis, is Sun pointed)

The injection uncertainties at the TIP (first launch, 99.89 degree launch azimuth) are given in Table 9.1-2B. They are referenced to an upper stage spin of 60 rpm, a time constant of 55 s and a probability of command shut-down of the second stage (PCS) of 97.9%.

TABLE 9.1-2B MGS INJECTION COVARIANCE

```
INJECTION COVARIANCE
MANDAT='20-NOV-1996 22:00:46.7000',
INJDAT='05-NOV-1996 19:09:56.5662',
CODE='TNR',
UNIT='FTFPS'
COV =
.42186182E+10, -.17043019E+07,  .15952328E+09,  .46986249E+05,  .17151895E+04,
                                                               -.44555790E+07,
.31940420E+07,  .66542398E+05, -.16566485E+03, -.78389002E+04,  .17337354E+04,
.25080867E+08, -.14994659E+05, -.34278865E+03, -.15938287E+06,
.13323435E+03, -.26089190E+02, -.25563465E+03,
.30815324E+04, -.36564384E+01,
,77604440E+04,
;
```

NOTES: 1. The above covariance corresponds to the Nov. 5, 1996 LAUNCH DATE in the TNR or NASA coordinate system in FT, FT PER SEC units.
This is what is received from McDonnell Douglas Aerospace.

2. NASA COORDINATE SYSTEM DEFINITION:
The origin is at the vehicle's nominal present position. The positive x-axis is parallel to the projection of the nominal inertial velocity onto a plane perpendicular to the nominal radius vector. The z-axis is positive away from the earth along the nominal radius vector. The y-axis completes the right-handed orthogonal system.

3. The above covariance corresponds to the THIRD STAGE NOMINAL SPIN RATE OF 60 RPM AND NUTATION TIME CONSTANT OF 55 SEC.

9.2 SPACECRAFT CONFIGURATION

The spacecraft's injected mass used in the interplanetary phase analysis is 1060. kg.

The spacecraft's configuration during the interplanetary, orbit insertion and mapping orbit phases (without flaps) is shown in Figure 9.2-1.

Fig 9.2-1 Spacecraft configuration.

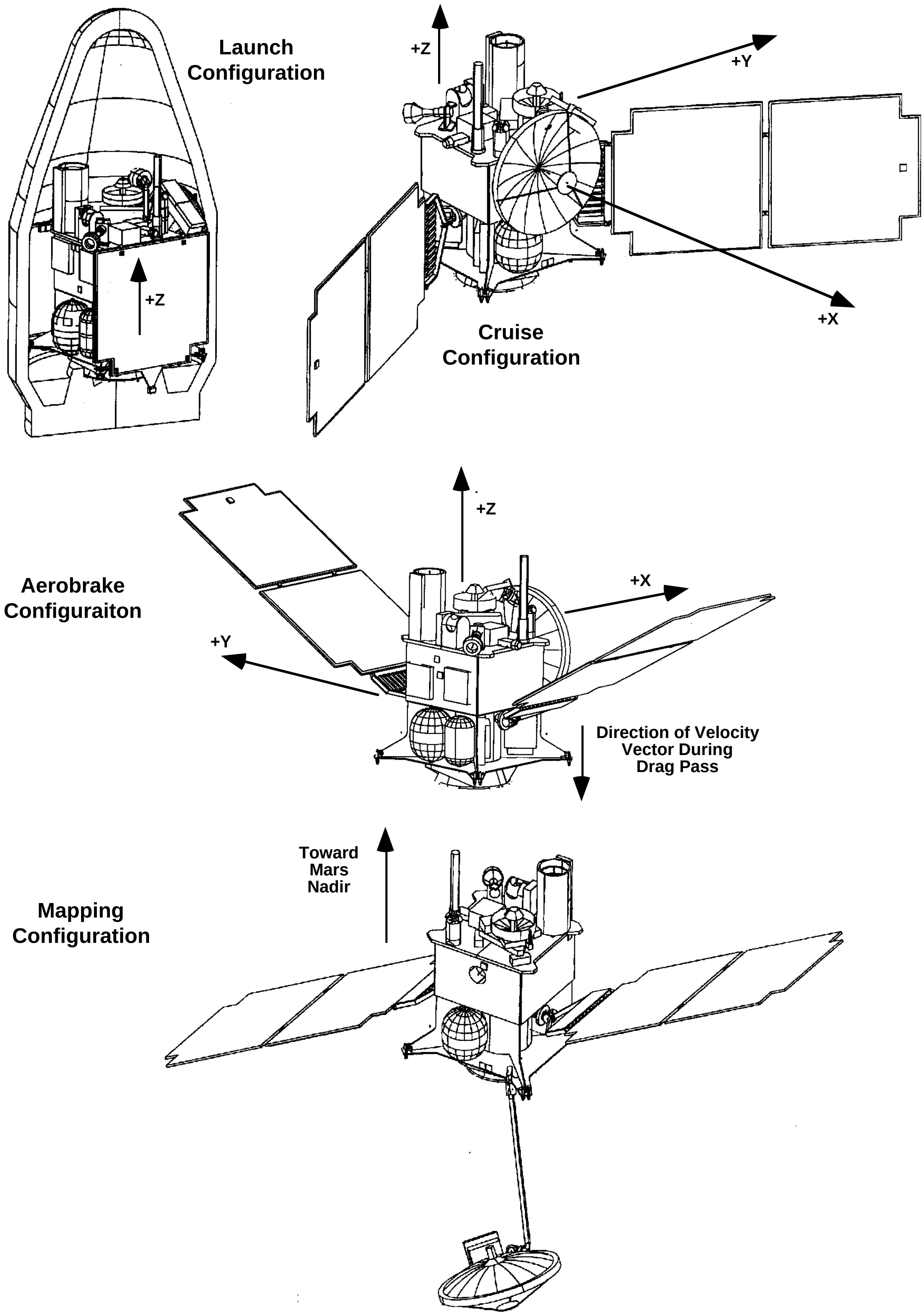


Figure 9.2-1 Spacecraft Configuration

APPENDIX 9.3 MARS POSITION AND VELOCITY UNCERTAINTY AT ENCOUNTER

9.3-A Previous Mars Ephemeris, Used in Analysis

In general, at JPL, an assessment of error associated with planetary orbits is given in terms of the Brouwer and Clemence set III orbital elements. In addition, the nominal epoch to which they apply is 06-28-1969 00:00:00 (JD = 2440400.50 days). The formal 12x12 earth-moon barycenter and Mars ephemeris covariance is given in reference 4.3 for DE 245 (Development Ephemeris 245).

In order to better understand the ephemeris errors, the planetary ephemeris covariance was transformed to heliocentric, cartesian coordinates. Table 9.3-1A gives the RSS (root-sum-square) position and velocity errors at encounter.

TABLE 9.3-1A RSS HELIOCENTRIC POSITION AND VELOCITY UNCERTAINTY (ONE SIGMA) OF THE EARTH-MOON BARYCENTER AND MARS

	Earth-Moon Barycenter		Mars	
Epoch	Position (km)	Velocity (mm/s)	Position (km)	Velocity (mm/s)
09/11/97	10.1	2.0	14.8	1.6

Table 9.3-2A gives planetary position and velocity errors in a heliocentric, inertial, cartesian coordinate system, defined by the radial, downtrack and crosstrack components. This shows that the radial distance is well known. In comparison, the orientation of the orbital plane and the position of the planet in the orbital plane (downtrack error) are known less well.

TABLE 9.3-2A HELIOCENTRIC POSITION AND VELOCITY COMPONENT UNCERTAINTIES (ONE SIGMA) OF THE EARTH-MOON BARYCENTER AND MARS AT ENCOUNTER (09/11/97)

	Position (km)			Velocity (mm/s)		
	Radial	Down track	Cross track	Radial	Down track	Cross track
Earth-Moon Barycenter	0.023	7.0	7.3	1.4	0.02	1.4
Mars	0.34	10.4	10.5	1.2	0.1	1.2

9.3-B Updated Mars Ephemeris

In general, at JPL, an assessment of error associated with planetary orbits is given in terms of the Brouwer and Clemence set III orbital elements. In addition, the nominal epoch to which they apply is 06-28-1969 00:00:00 (JD = 2440400.50 days). The DE 403 (Development Ephemeris 403) formal 12x12 earth-moon barycenter and Mars ephemeris and covariance is documented in JPL IOM 314.10-127 (5/22/95) and e-mail from E. M. Standish dated 10/13/95.

In order to better understand the ephemeris errors, the planetary ephemeris covariance was transformed to heliocentric, cartesian coordinates. Table 9.3-1B gives the RSS (root-sum-square) position and velocity errors at encounter.

TABLE 9.3-1B RSS HELIOCENTRIC POSITION AND VELOCITY UNCERTAINTY (ONE SIGMA) OF THE EARTH-MOON BARYCENTER AND MARS

Epoch	Earth-Moon Barycenter Position (km)	Earth-Moon Barycenter Velocity (mm/s)	Mars Position (km)	Mars Velocity (mm/s)
09/11/97	3.4	0.76	5.7	0.57

Table 9.3-2B gives planetary position and velocity errors in a heliocentric, inertial, cartesian coordinate system, defined by the radial, downtrack and crosstrack components. This shows that the radial distance is well known. In comparison, the orientation of the orbital plane and the position of the planet in the orbital plane (downtrack error) are known less well.

TABLE 9.3-2B HELIOCENTRIC POSITION AND VELOCITY COMPONENT UNCERTAINTIES (ONE SIGMA) OF THE EARTH-MOON BARYCENTER AND MARS AT ENCOUNTER (09/11/97)

	Position (km)			Velocity (mm/s)		
	Radial	Down track	Cross track	Radial	Down track	Cross track
Earth-Moon Barycenter	0.008	2.35	2.42	0.46	0.007	0.61
Mars	0.09	3.50	4.47	0.40	0.034	0.41

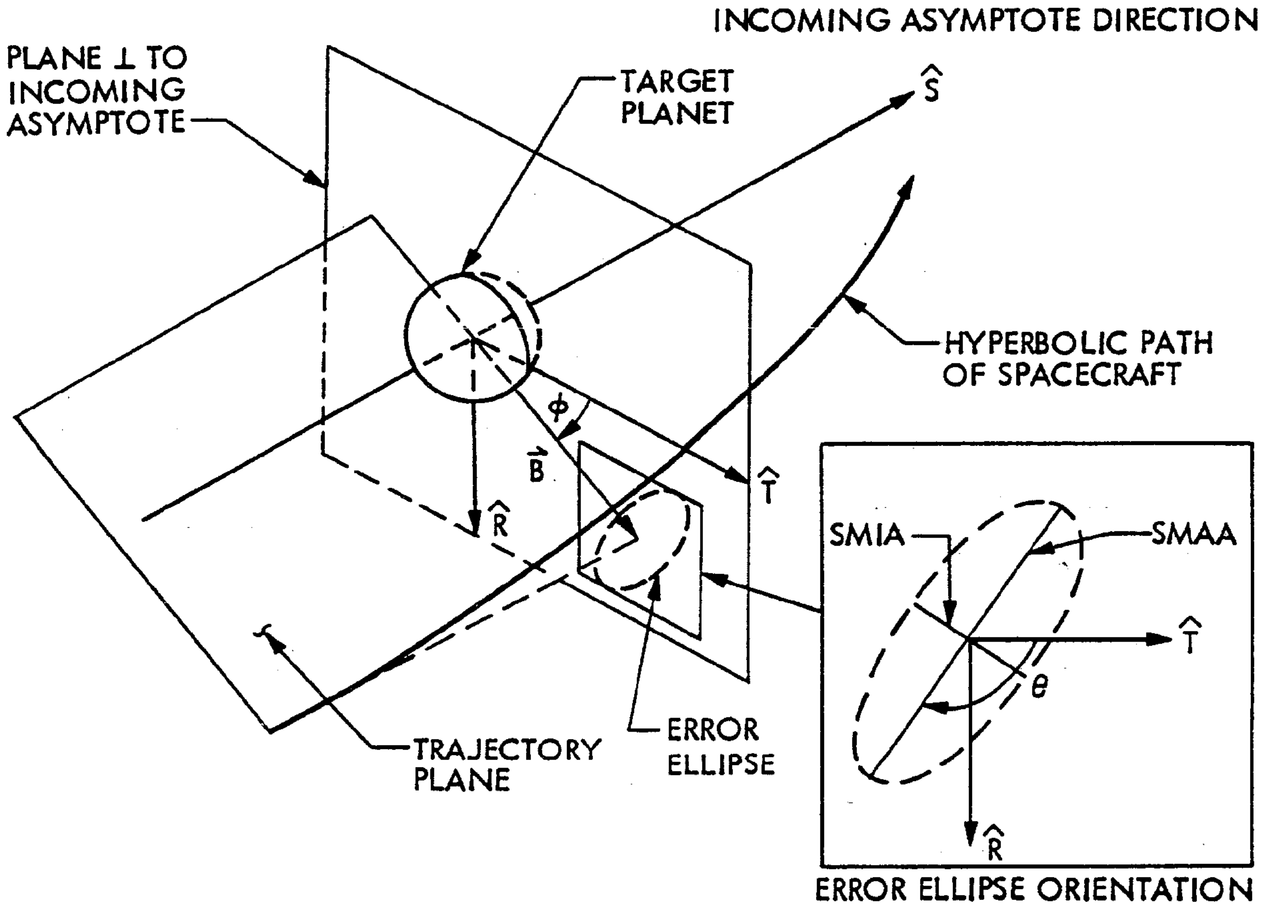
APPENDIX 9.4 MARS TARGET OR B-PLANE DEFINITION

The Mars centered targeting or encounter coordinate system in (Fig. 9.4-1) which the target parameters (i.e. B vector as shown and time of encounter) are expressed is commonly referred to as the B-plane.

Coordinates are defined by three orthogonal unit vectors, S, T, and R with the system origin at the center of the target body. The S vector is parallel to the spacecraft's velocity at infinity (V_∞) vector. T is defined to be in Mars' equatorial plane and perpendicular to S and R completes an orthogonal triad with S and T (**R** = **S** x **T**).

Trajectory uncertainties in the B-plane are often characterized by a one-sigma uncertainty or dispersion ellipse as shown. SMAA and SMIA denote the semi-major and semi-minor axes of the ellipse; θ is the angle measured clockwise from the T axis to SMAA. The uncertainty normal to the B-plane is typically given as a one-sigma time-of-flight, where time-of-flight specifies what the time to encounter would be from some given epoch if the magnitude of the B-vector were zero. Alternatively, these dispersions are sometimes given as a one-sigma distance uncertainty along the S direction, numerically equal to the time-of-flight uncertainty multiplied by the magnitude of the velocity-at-infinity.

Fig. 9.4-1 B-Plane description.



$\vec{B}$ = MISS PARAMETER = $\frac{1}{V_\infty}(\hat{S} \times \vec{H})$, i.e., $\vec{B} \times (V_\infty \hat{S}) = \vec{H}$

$\vec{H}$ = ANGULAR MOMENTUM VECTOR

V_∞ = VELOCITY AT INFINITY

$\hat{T}$ = PARALLEL TOEQUATOR PLANE AND NORMAL TO $\hat{S}$

$\hat{R} = \hat{S} \times \hat{T}$

Figure 9.4-1 B-Plane Description

APPENDIX 9.5 MARS GRAVITY FIELD AND UNCERTAINTIES

The Mars gravity field model used by navigation in this Navigation Plan is the Goddard Mars Model 1 or GMM-1. It is described in Appendix 9.5 of the MGS Navigation Plan, Rev. A (9/15/95). However, it has been decided to use a newer gravity field in operations: JPL Mars 50C or MARS50C (Ref 4.10). This is the model that will be described here. It has replaced the 18th degree and order field due to Balmino et. al (Ref 9.1) previously used in the Mars Observer Navigation Plan. It has also replaced the 50th degree and order field from Goddard (Ref 4.9) described in the MGS Final Navigation Plan, Rev. A.

The gravity field depends on the constants assumed while generating it. Constants consistent with the MARS50C gravity field are as follows. (These are mostly consistent with the 1991 IAU planetary constants report (Ref 9.2).)

1) GM(Mars) = 42828.357 964 77 km^3/s^2 $\pm$ 0.00859 km^3/s^2 (1 σ)
2) Mars mean equatorial radius = 3394.2 km
3) Angle from ascending node to Mars prime meridian (at January 1.5, 20000 = J2000) = 176.868 deg
4) Mean sidereal rotation rate = 350.8919830 deg/day
5) Right ascension of mean north pole at J2000 (in EME 2000) = 317.681 deg
6) Rate of change of right ascension = -0.108 deg / Julian century
7) Declination of mean north pole at J2000 (in EME 2000) = 52.886 deg
8) Rate of change of declination = -0.061 deg / Julian century

For reference, we give a tabulation of the normalized gravity field coefficients and their one-sigma uncertainties as an attached file.

Gravity Coeff.	Coefficient Value	Coefficient Error
J402	8.7591976e-04	1.346285e-08
C40201	1.3203347e-08	3.065939e-09
S40201	6.7528529e-10	3.170672e-09
C40202	-8.4312202e-05	2.229742e-09
S40202	4.9678533e-05	2.294473e-09
J403	1.1934068e-05	2.089515e-08
C40301	3.8656770e-06	7.771579e-09
S40301	2.5277425e-05	7.839380e-09
C40302	-1.5925790e-05	7.966472e-09
S40302	8.4668729e-06	7.781345e-09
C40303	3.5414127e-05	3.674303e-09
S40303	2.5199663e-05	3.595425e-09
J404	-5.1505249e-06	3.114195e-08
C40401	4.2392077e-06	1.394790e-08
S40401	3.7475558e-06	1.503367e-08
C40402	-1.1164682e-06	1.159914e-08
S40402	-8.9633910e-06	1.165423e-08
C40403	6.5141872e-06	8.591571e-09
S40403	-2.7235242e-07	8.175882e-09
C40404	1.1300298e-07	6.401294e-09
S40404	-1.2895390e-05	6.522668e-09
J405	1.8240290e-06	4.658390e-08
C40501	4.8331974e-07	2.328693e-08
S40501	2.0971116e-06	2.395688e-08
C40502	-4.2495088e-06	1.766212e-08
S40502	-1.2248091e-06	1.841221e-08
C40503	3.3031470e-06	1.540642e-08
S40503	2.5419126e-07	1.591695e-08
C40504	-4.6875858e-06	1.184332e-08
S40504	-3.3259226e-06	1.154753e-08
C40505	-4.4218049e-06	7.776370e-09
S40505	3.8360542e-06	7.896598e-09
J406	-1.4566597e-06	7.190405e-08
C40601	1.8929215e-06	3.778934e-08
S40601	-1.6257586e-06	3.862636e-08
C40602	9.5288171e-07	2.697155e-08
S40602	1.6124720e-06	2.596421e-08
C40603	9.5131352e-07	2.608839e-08
S40603	2.4405057e-07	2.561870e-08
C40604	1.0349697e-06	1.813490e-08
S40604	2.6518533e-06	1.796707e-08
C40605	1.7817524e-06	1.520379e-08
S40605	1.6289712e-06	1.525698e-08
C40606	2.7852984e-06	1.007918e-08
S40606	7.8534640e-07	9.778528e-09
J407	-8.4012881e-07	1.117691e-07
C40701	1.1439266e-06	5.646627e-08
S40701	-1.2142472e-07	5.722753e-08
C40702	2.7991367e-06	4.699301e-08
S40702	-7.3191605e-07	4.495711e-08
C40703	8.4038965e-07	3.851394e-08
S40703	-4.2372322e-07	3.806806e-08
C40704	2.3981952e-06	2.928565e-08
S40704	-5.2598370e-07	2.859388e-08
C40705	-3.0877205e-07	2.158247e-08
S40705	-1.3347427e-06	2.232501e-08
C40706	-5.7230195e-07	1.790389e-08
S40706	-1.9362713e-06	1.791763e-08
C40707	4.1919855e-07	1.319798e-08
S40707	-1.7712231e-06	1.228182e-08
J408	-4.9831605e-07	1.641049e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
C40801	2.0285603e-07	8.507321e-08
S40801	6.2615110e-07	8.735646e-08
C40802	1.6675997e-06	7.694985e-08
S40802	6.5912851e-07	7.402811e-08
C40803	-1.0871239e-06	5.445446e-08
S40803	-1.3272973e-06	5.426296e-08
C40804	1.6265110e-06	4.357723e-08
S40804	4.1543012e-08	4.349571e-08
C40805	-2.7955426e-06	3.460369e-08
S40805	-1.6262943e-06	3.409635e-08
C40806	-1.0069247e-06	2.512426e-08
S40806	-1.7674145e-06	2.452422e-08
C40807	-4.9370906e-07	2.133459e-08
S40807	1.6561810e-06	2.182848e-08
C40808	-3.0606856e-07	1.493684e-08
S40808	-2.6387169e-07	1.432681e-08
J409	7.3862700e-07	2.314217e-07
C40901	1.4036359e-08	1.217074e-07
S40901	-2.0751680e-07	1.229219e-07
C40902	1.1984449e-06	1.213817e-07
S40902	1.5469927e-07	1.180552e-07
C40903	-1.1677325e-06	8.049435e-08
S40903	-8.9421727e-07	8.146813e-08
C40904	4.0377295e-07	6.731560e-08
S40904	1.6965407e-06	6.614441e-08
C40905	-2.3714699e-06	4.949406e-08
S40905	-1.5066898e-06	5.063032e-08
C40906	8.9091157e-07	3.746879e-08
S40906	5.6762069e-07	3.862779e-08
C40907	-5.4418413e-07	2.820176e-08
S40907	9.2728877e-07	2.841527e-08
C40908	1.1962309e-06	2.399045e-08
S40908	-1.7632626e-07	2.427809e-08
C40909	-1.2239821e-06	1.712484e-08
S40909	-6.2179613e-07	1.840998e-08
J410	-1.3777859e-06	2.989708e-07
C41001	1.5878645e-06	1.648726e-07
S41001	-2.5576358e-07	1.665578e-07
C41002	-4.9183652e-08	1.790618e-07
S41002	-9.7969391e-07	1.752755e-07
C41003	-2.7973877e-08	1.167289e-07
S41003	3.2151708e-07	1.179722e-07
C41004	-1.2144493e-06	9.981155e-08
S41004	-3.3900965e-08	1.011310e-07
C41005	4.8801077e-07	7.492830e-08
S41005	-8.1660419e-07	7.412472e-08
C41006	5.2419709e-07	5.482156e-08
S41006	1.1369890e-06	5.715423e-08
C41007	2.4189305e-07	4.202995e-08
S41007	-7.1118300e-07	4.150158e-08
C41008	5.4207688e-07	3.211517e-08
S41008	8.1044307e-07	3.129406e-08
C41009	-1.5754742e-06	2.770964e-08
S41009	-1.4585346e-06	2.799069e-08
C41010	-2.1466868e-07	2.100603e-08
S41010	8.0404739e-07	1.853271e-08
J411	8.9984399e-07	3.621871e-07
C41101	-1.7039179e-06	2.100823e-07
S41101	2.3597458e-07	2.141645e-07
C41102	-3.1742036e-07	2.367838e-07
S41102	-1.1116145e-06	2.331730e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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C41103	-1.7808977e-06	1.584236e-07
S41103	8.7469715e-07	1.593221e-07
C41104	-1.6842800e-06	1.434186e-07
S41104	-5.2697489e-07	1.455747e-07
C41105	9.8494672e-07	1.077532e-07
S41105	4.9911879e-07	1.057459e-07
C41106	-3.9588879e-08	8.032085e-08
S41106	1.3557360e-08	8.369711e-08
C41107	8.6593271e-07	6.250351e-08
S41107	-8.8352192e-07	6.258909e-08
C41108	-1.1046819e-06	4.620367e-08
S41108	8.2847043e-07	4.575082e-08
C41109	-3.5311851e-07	3.558560e-08
S41109	-3.9036970e-07	3.538497e-08
C41110	4.0255599e-07	3.059337e-08
S41110	1.9127301e-06	2.907356e-08
C41111	-1.9847868e-09	2.194806e-08
S41111	-3.5177095e-07	2.419668e-08
J412	-9.6560412e-07	3.857747e-07
C41201	-3.2051508e-07	2.553192e-07
S41201	-5.4388362e-07	2.577821e-07
C41202	-2.2951967e-07	2.783728e-07
S41202	8.0302711e-07	2.752555e-07
C41203	-9.3491688e-07	2.016132e-07
S41203	1.5940961e-07	2.024918e-07
C41204	-2.0860392e-07	1.847360e-07
S41204	-8.8010079e-08	1.870875e-07
C41205	1.3088140e-06	1.483299e-07
S41205	1.4056243e-06	1.477133e-07
C41206	-6.7317825e-07	1.135117e-07
S41206	-1.5708349e-06	1.130560e-07
C41207	2.9451732e-07	9.216062e-08
S41207	-1.5822825e-07	9.096796e-08
C41208	-1.7022671e-06	6.797857e-08
S41208	-3.9645289e-07	7.035666e-08
C41209	8.0347599e-07	5.023791e-08
S41209	4.8998780e-07	5.148593e-08
C41210	5.3893624e-07	3.986437e-08
S41210	1.4378981e-06	3.620378e-08
C41211	7.5045384e-07	3.254996e-08
S41211	-1.5625319e-06	3.305062e-08
C41212	-1.0842694e-08	2.589429e-08
S41212	-1.2762569e-07	2.579030e-08
J413	8.7964298e-07	3.747706e-07
C41301	-1.1615765e-06	2.841255e-07
S41301	7.2716501e-07	2.809506e-07
C41302	1.9940713e-07	2.902427e-07
S41302	6.3076661e-07	2.879046e-07
C41303	-1.7031104e-07	2.347412e-07
S41303	5.2832944e-07	2.358822e-07
C41304	3.5748830e-07	2.157183e-07
S41304	8.3426915e-07	2.181392e-07
C41305	-6.7182446e-07	1.838261e-07
S41305	-9.0878821e-07	1.861570e-07
C41306	3.2994696e-07	1.500804e-07
S41306	-9.3622767e-07	1.486742e-07
C41307	-5.4594506e-07	1.215598e-07
S41307	5.4089435e-07	1.206238e-07
C41308	-1.2138363e-08	9.789875e-08
S41308	9.0094562e-08	9.940111e-08
C41309	1.0180645e-06	7.800785e-08
S41309	9.2504710e-07	7.708865e-08
C41310	-8.3227615e-08	5.441051e-08
S41310	-7.4062579e-07	5.182396e-08
C41311	8.1883405e-07	4.099148e-08
S41311	-9.3165487e-07	4.135222e-08
C41312	-1.4861378e-06	3.478660e-08
S41312	-3.3759378e-07	3.558585e-08
C41313	4.9042307e-07	2.864760e-08
S41313	8.5438814e-07	3.026488e-08
J414	-6.9873478e-07	3.165693e-07
C41401	1.1398907e-06	2.804843e-07
S41401	8.3642339e-08	2.766264e-07
C41402	3.9656786e-07	2.719920e-07
S41402	-3.5916323e-07	2.715265e-07
C41403	7.3802926e-07	2.412077e-07
S41403	-5.8977602e-07	2.424146e-07
C41404	-6.4758481e-08	2.279701e-07
S41404	-9.5364626e-07	2.302857e-07
C41405	3.7763149e-07	2.042599e-07
S41405	-4.6096166e-07	2.100259e-07
C41406	-3.9100996e-07	1.800021e-07
S41406	-6.1640400e-09	1.781132e-07
C41407	-8.8065079e-07	1.490010e-07
S41407	2.3599942e-07	1.502929e-07
C41408	5.6647621e-07	1.262393e-07
S41408	3.6844097e-07	1.269676e-07
C41409	2.1558012e-07	1.100935e-07
S41409	9.1846377e-07	1.109137e-07
C41410	-2.4615676e-07	7.895994e-08
S41410	-1.4420899e-06	7.976456e-08
C41411	-8.8938405e-07	5.580237e-08
S41411	1.8665204e-07	5.530818e-08
C41412	-4.9356850e-07	4.455778e-08
S41412	-3.6127164e-07	4.302338e-08
C41413	9.4350965e-07	3.869051e-08
S41413	1.9837832e-06	3.925524e-08
C41414	-2.5103505e-08	3.358892e-08
S41414	-7.6952074e-07	3.182234e-08
J415	-5.4425650e-07	2.651393e-07
C41501	4.8836824e-08	2.471590e-07
S41501	2.7500044e-07	2.437799e-07
C41502	-4.1994095e-07	2.372589e-07
S41502	-8.4943694e-07	2.382774e-07
C41503	-8.2380847e-07	2.225234e-07
S41503	-1.4580580e-07	2.239710e-07
C41504	-6.8409279e-07	2.213816e-07
S41504	-7.9334303e-07	2.214168e-07
C41505	-1.6303308e-06	2.025691e-07
S41505	-6.9843051e-07	2.074237e-07
C41506	6.7825467e-08	1.948261e-07
S41506	5.4870227e-07	1.934307e-07
C41507	1.2884430e-06	1.676090e-07
S41507	2.0193477e-07	1.662242e-07
C41508	1.3756016e-06	1.482433e-07
S41508	4.6401435e-07	1.478998e-07
C41509	-3.0830954e-07	1.397133e-07
S41509	-3.4328047e-07	1.407051e-07
C41510	-5.0047414e-08	1.091481e-07
S41510	-4.1425622e-07	1.119437e-07
C41511	-9.1500424e-07	7.903590e-08
S41511	6.5749010e-07	7.946694e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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C41512	9.9805144e-07	5.777168e-08
S41512	7.1842511e-07	5.788043e-08
C41513	-1.9526595e-08	4.883966e-08
S41513	6.9713099e-07	4.745596e-08
C41514	8.9535448e-08	4.314453e-08
S41514	-1.3735917e-06	4.231318e-08
C41515	-3.9190400e-07	3.511370e-08
S41515	1.0965463e-07	3.787269e-08
J416	-7.9272066e-07	2.260247e-07
C41601	-1.4657144e-07	2.041661e-07
S41601	-4.7798619e-07	2.065510e-07
C41602	-4.3383613e-07	2.031545e-07
S41602	-9.1932204e-08	2.040499e-07
C41603	-5.1979067e-07	1.936172e-07
S41603	2.4296092e-07	1.943785e-07
C41604	-8.9545902e-07	1.994420e-07
S41604	4.8761024e-08	1.971162e-07
C41605	2.0715456e-07	1.881825e-07
S41605	6.9588931e-07	1.915142e-07
C41606	2.3143190e-07	1.896877e-07
S41606	1.5896402e-07	1.869744e-07
C41607	2.1234036e-07	1.733676e-07
S41607	2.6026098e-07	1.718413e-07
C41608	6.9732754e-08	1.557859e-07
S41608	3.2000493e-07	1.558141e-07
C41609	-2.1626911e-07	1.557423e-07
S41609	-1.0653599e-06	1.564145e-07
C41610	-5.9008608e-07	1.378393e-07
S41610	4.7147781e-07	1.413983e-07
C41611	1.0392734e-08	1.086078e-07
S41611	-4.6128756e-07	1.086518e-07
C41612	4.9566018e-07	7.826633e-08
S41612	7.2431022e-07	7.734242e-08
C41613	9.7322633e-08	6.164400e-08
S41613	-6.6949662e-07	6.230944e-08
C41614	-1.3495432e-07	5.287523e-08
S41614	-8.5270335e-07	5.227527e-08
C41615	-7.6392362e-07	4.659213e-08
S41615	3.7879395e-07	4.853394e-08
C41616	2.6813624e-07	4.438893e-08
S41616	6.6088305e-08	3.647254e-08
J417	-3.0321378e-07	2.137497e-07
C41701	-1.2395077e-07	1.945902e-07
S41701	-8.9613880e-07	2.011640e-07
C41702	-5.7508383e-08	1.812768e-07
S41702	1.7543149e-07	1.788479e-07
C41703	6.7591058e-08	1.794537e-07
S41703	1.3715685e-07	1.810582e-07
C41704	5.3121316e-07	1.764384e-07
S41704	4.4460836e-08	1.724002e-07
C41705	5.5065667e-07	1.709874e-07
S41705	3.4398805e-07	1.743946e-07
C41706	7.3159707e-07	1.716615e-07
S41706	-1.7116624e-07	1.698769e-07
C41707	5.8206904e-07	1.664648e-07
S41707	-3.5575325e-07	1.685306e-07
C41708	-1.3306995e-07	1.553070e-07
S41708	-2.4780069e-07	1.554537e-07
C41709	-1.8107689e-07	1.563668e-07
S41709	-1.2222911e-07	1.552257e-07
C41710	-3.3088174e-07	1.531180e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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S41710	9.2901476e-08	1.537087e-07
C41711	3.1559477e-07	1.365549e-07
S41711	6.6505630e-08	1.350981e-07
C41712	1.3870383e-07	1.031790e-07
S41712	-3.7523763e-08	1.023367e-07
C41713	-4.8889728e-07	7.938305e-08
S41713	-6.2508165e-07	7.844527e-08
C41714	-3.5779161e-07	6.837515e-08
S41714	-4.1046683e-07	6.548858e-08
C41715	-3.5586205e-07	5.789611e-08
S41715	5.2771335e-07	5.931913e-08
C41716	1.1309390e-06	5.555049e-08
S41716	5.5189609e-07	5.102987e-08
C41717	1.0790003e-07	4.368202e-08
S41717	3.3781942e-07	4.528737e-08
J418	3.0301463e-07	2.183753e-07
C41801	-3.2242794e-07	2.068754e-07
S41801	-1.4489743e-07	2.159468e-07
C41802	-1.6548964e-07	1.792208e-07
S41802	1.6758395e-07	1.771074e-07
C41803	-4.5057586e-07	1.824406e-07
S41803	-4.1931930e-07	1.849015e-07
C41804	7.7040959e-07	1.659211e-07
S41804	3.0499471e-07	1.616117e-07
C41805	2.7247187e-07	1.650085e-07
S41805	-7.0592927e-07	1.682773e-07
C41806	1.1205111e-07	1.557513e-07
S41806	-6.0305797e-07	1.562580e-07
C41807	-2.6728099e-07	1.552813e-07
S41807	1.9469692e-08	1.586898e-07
C41808	-5.3266733e-08	1.487941e-07
S41808	-2.4232529e-07	1.491814e-07
C41809	-3.5883487e-08	1.500259e-07
S41809	2.2744523e-07	1.479744e-07
C41810	5.3362979e-07	1.483491e-07
S41810	2.0216455e-07	1.501833e-07
C41811	3.8443519e-07	1.463292e-07
S41811	-2.3477468e-07	1.477711e-07
C41812	5.7185438e-08	1.246425e-07
S41812	-4.1196691e-08	1.260558e-07
C41813	-3.4862696e-07	9.959342e-08
S41813	-1.7529273e-07	9.894625e-08
C41814	-4.9980409e-07	8.309168e-08
S41814	2.1669904e-07	8.006145e-08
C41815	3.4793074e-07	7.024003e-08
S41815	7.7308420e-07	7.558175e-08
C41816	4.2462835e-07	6.735993e-08
S41816	1.5595455e-07	6.381823e-08
C41817	-1.6022556e-07	5.870850e-08
S41817	-1.0824964e-06	5.866112e-08
C41818	5.0252671e-07	5.188572e-08
S41818	3.0687979e-07	4.595037e-08
J419	-3.0836739e-07	2.225577e-07
C41901	4.3165338e-07	2.108108e-07
S41901	3.6074996e-07	2.215066e-07
C41902	-9.7569931e-08	1.964535e-07
S41902	1.3621701e-07	1.956173e-07
C41903	1.4290542e-08	1.897791e-07
S41903	-2.1802385e-07	1.917457e-07
C41904	-4.3718238e-08	1.783564e-07
S41904	4.2977086e-07	1.733091e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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C41905	5.4313870e-08	1.664120e-07
S41905	-3.5681161e-07	1.679945e-07
C41906	-1.5946884e-07	1.553689e-07
S41906	-8.2664738e-08	1.574286e-07
C41907	-4.2764722e-07	1.468613e-07
S41907	1.2748186e-07	1.502042e-07
C41908	2.9371966e-07	1.456945e-07
S41908	-1.4487339e-07	1.460853e-07
C41909	1.4230257e-07	1.409946e-07
S41909	3.7216086e-07	1.405980e-07
C41910	6.3732501e-07	1.406195e-07
S41910	-1.8802101e-07	1.401852e-07
C41911	-2.8341468e-07	1.440647e-07
S41911	-3.9842193e-07	1.441338e-07
C41912	-2.3914459e-07	1.358952e-07
S41912	-1.4517121e-07	1.356045e-07
C41913	-2.4570987e-07	1.175054e-07
S41913	-8.4603890e-08	1.183510e-07
C41914	2.1278687e-07	1.002311e-07
S41914	4.4785097e-07	9.776543e-08
C41915	6.8352904e-07	8.434077e-08
S41915	4.3837482e-07	8.855709e-08
C41916	-1.4609718e-07	8.350292e-08
S41916	-1.8864359e-07	7.788369e-08
C41917	-1.5487047e-07	7.273171e-08
S41917	-7.4909316e-07	7.291793e-08
C41918	-6.1512308e-07	7.088351e-08
S41918	5.3579130e-07	6.305385e-08
C41919	-4.1223977e-07	5.377257e-08
S41919	-8.1343982e-07	5.138887e-08
J420	-3.6625705e-07	2.178203e-07
C42001	1.9490309e-07	2.010266e-07
S42001	4.3743256e-07	2.105320e-07
C42002	6.1089916e-08	1.993857e-07
S42002	-2.8941098e-07	1.959864e-07
C42003	1.1839287e-07	1.862073e-07
S42003	2.0437172e-07	1.884696e-07
C42004	-2.2288649e-07	1.878634e-07
S42004	4.0062991e-07	1.831523e-07
C42005	-6.7715087e-08	1.736258e-07
S42005	-7.6127484e-08	1.757921e-07
C42006	2.8758604e-07	1.681972e-07
S42006	6.2972592e-07	1.688472e-07
C42007	2.4527553e-07	1.511551e-07
S42007	-3.2557249e-07	1.567831e-07
C42008	4.2614346e-07	1.463441e-07
S42008	1.6664864e-07	1.469148e-07
C42009	-4.6261846e-08	1.406971e-07
S42009	9.3672449e-08	1.405489e-07
C42010	-3.7359569e-07	1.352004e-07
S42010	-3.3694235e-08	1.355036e-07
C42011	-1.1904721e-08	1.358077e-07
S42011	-8.4750535e-08	1.353408e-07
C42012	-4.4064072e-07	1.365504e-07
S42012	-5.9821306e-09	1.361603e-07
C42013	6.0940648e-08	1.276990e-07
S42013	2.1623943e-07	1.291953e-07
C42014	3.7510250e-07	1.142645e-07
S42014	1.6854757e-07	1.153199e-07
C42015	2.8424895e-07	9.873352e-08
S42015	-4.2306734e-07	1.039618e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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C42016	2.3574698e-07	9.239147e-08
S42016	-2.5271787e-07	9.352300e-08
C42017	-2.0938586e-07	8.816216e-08
S42017	-2.9755447e-08	8.903084e-08
C42018	5.1815655e-08	8.568788e-08
S42018	7.2262495e-07	8.196929e-08
C42019	2.6590246e-07	7.146469e-08
S42019	-1.3895274e-07	7.308144e-08
C42020	-4.3242212e-07	5.625347e-08
S42020	1.8528236e-07	5.818725e-08
J421	-1.3616279e-07	1.989002e-07
C42101	-1.9733757e-07	1.956202e-07
S42101	-9.2423930e-08	1.993397e-07
C42102	1.7246639e-07	1.906233e-07
S42102	-3.0236447e-07	1.877817e-07
C42103	-1.2040083e-07	1.884497e-07
S42103	1.0179395e-07	1.892868e-07
C42104	-1.8400188e-07	1.843607e-07
S42104	2.4861032e-08	1.793868e-07
C42105	5.0665526e-07	1.747511e-07
S42105	1.4033948e-07	1.771716e-07
C42106	9.6997032e-08	1.674580e-07
S42106	2.1051144e-07	1.681873e-07
C42107	1.5231027e-07	1.606683e-07
S42107	-3.8907182e-07	1.651091e-07
C42108	-1.8282706e-08	1.515624e-07
S42108	2.2085109e-07	1.515323e-07
C42109	-1.2637233e-07	1.484146e-07
S42109	-1.9534965e-07	1.471518e-07
C42110	-3.6501062e-07	1.384163e-07
S42110	2.0033214e-07	1.409404e-07
C42111	-1.7720699e-07	1.328908e-07
S42111	-2.3412010e-07	1.325288e-07
C42112	1.7585929e-07	1.330599e-07
S42112	-5.3710494e-08	1.302570e-07
C42113	1.1691439e-07	1.308364e-07
S42113	1.6870313e-07	1.313773e-07
C42114	1.1158020e-07	1.243707e-07
S42114	-3.6520980e-07	1.247060e-07
C42115	-3.5718394e-07	1.129036e-07
S42115	-5.1997704e-07	1.138209e-07
C42116	-4.0019206e-07	1.035149e-07
S42116	-1.4568677e-12	1.055684e-07
C42117	-3.1748646e-07	9.986848e-08
S42117	-3.0054803e-07	9.925871e-08
C42118	3.5165099e-07	1.003460e-07
S42118	5.8382171e-07	9.971157e-08
C42119	1.9383108e-08	9.031589e-08
S42119	-5.0268540e-07	9.089570e-08
C42120	-2.4957602e-07	8.298848e-08
S42120	-4.3942961e-07	7.879020e-08
C42121	7.3913467e-07	6.265235e-08
S42121	2.2968057e-07	5.971675e-08
J422	-1.5877199e-07	1.828386e-07
C42201	-1.6383620e-07	1.820122e-07
S42201	-2.0808554e-07	1.872910e-07
C42202	1.5846559e-07	1.784165e-07
S42202	1.7475570e-07	1.765417e-07
C42203	-2.4776659e-07	1.794781e-07
S42203	7.3104567e-08	1.807241e-07
C42204	1.7089104e-07	1.747445e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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S42204	-2.3937207e-07	1.707729e-07
C42205	1.0602806e-07	1.735010e-07
S42205	1.5252083e-07	1.772205e-07
C42206	-7.8321600e-08	1.665714e-07
S42206	-2.7018311e-07	1.684747e-07
C42207	4.0130588e-07	1.622458e-07
S42207	-3.6528066e-08	1.678582e-07
C42208	-1.8199275e-07	1.545225e-07
S42208	-2.5693320e-07	1.559730e-07
C42209	-4.0028158e-09	1.502265e-07
S42209	1.7725822e-07	1.483186e-07
C42210	-5.8779737e-08	1.436685e-07
S42210	3.9237728e-07	1.458225e-07
C42211	9.2536917e-08	1.385740e-07
S42211	-5.1949618e-08	1.385597e-07
C42212	3.7150755e-07	1.315797e-07
S42212	1.3326154e-07	1.305036e-07
C42213	-1.6380600e-07	1.283526e-07
S42213	-1.5526745e-07	1.297294e-07
C42214	-5.2030570e-09	1.268825e-07
S42214	-5.4348912e-07	1.292333e-07
C42215	-3.3340136e-07	1.210633e-07
S42215	2.4270595e-07	1.217609e-07
C42216	-1.3116944e-07	1.104623e-07
S42216	-6.6501895e-08	1.146905e-07
C42217	1.8674818e-07	1.063813e-07
S42217	2.0492121e-07	1.080241e-07
C42218	-1.5060559e-07	1.067351e-07
S42218	1.3230486e-07	1.075137e-07
C42219	2.8131668e-07	1.074533e-07
S42219	-6.8684001e-07	1.059639e-07
C42220	-3.7684340e-07	1.030772e-07
S42220	1.8886895e-07	9.875762e-08
C42221	2.3521520e-07	8.133370e-08
S42221	6.5143458e-07	8.942179e-08
C42222	-2.2662922e-07	6.390884e-08
S42222	-4.1350456e-07	6.604136e-08
J423	-1.2636870e-08	1.735089e-07
C42301	1.2317190e-07	1.645558e-07
S42301	2.8016773e-07	1.699968e-07
C42302	1.1014841e-07	1.718330e-07
S42302	4.1842592e-07	1.705964e-07
C42303	-2.1254401e-08	1.639607e-07
S42303	-7.8028697e-08	1.651832e-07
C42304	3.2141982e-07	1.690787e-07
S42304	1.8051689e-09	1.650412e-07
C42305	-3.3765074e-07	1.592725e-07
S42305	3.9658669e-08	1.629408e-07
C42306	1.9775490e-07	1.605059e-07
S42306	-2.8420977e-07	1.630821e-07
C42307	-1.3006291e-07	1.541769e-07
S42307	1.3655936e-07	1.577274e-07
C42308	-1.9791551e-07	1.557313e-07
S42308	-2.3234939e-07	1.554169e-07
C42309	-9.8762166e-09	1.494239e-07
S42309	1.2185416e-07	1.482615e-07
C42310	-1.6054918e-07	1.438062e-07
S42310	2.9892555e-09	1.435804e-07
C42311	3.2595013e-07	1.380597e-07
S42311	-6.6333890e-08	1.397842e-07
C42312	-2.3616794e-07	1.343376e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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S42312	4.7212556e-08	1.316656e-07
C42313	-1.0117156e-07	1.268398e-07
S42313	3.5224940e-09	1.280349e-07
C42314	-1.4350340e-07	1.256433e-07
S42314	-1.8105188e-07	1.262395e-07
C42315	-1.8643266e-07	1.253350e-07
S42315	6.0414683e-07	1.232290e-07
C42316	4.4883036e-07	1.170155e-07
S42316	1.3972641e-07	1.179911e-07
C42317	4.1898145e-07	1.130633e-07
S42317	7.3241051e-07	1.087849e-07
C42318	-2.2772114e-07	1.062256e-07
S42318	-5.8948835e-07	1.109859e-07
C42319	5.2334786e-07	1.099843e-07
S42319	8.7932633e-08	1.067907e-07
C42320	-5.0509572e-07	1.127074e-07
S42320	7.9097547e-08	1.090653e-07
C42321	3.6265531e-07	1.003915e-07
S42321	6.6767539e-07	1.019802e-07
C42322	-1.7172894e-08	9.082743e-08
S42322	-1.2804691e-07	8.666279e-08
C42323	-6.3868191e-07	6.638214e-08
S42323	2.9359735e-07	6.897818e-08
J424	-5.7528683e-08	1.620157e-07
C42401	8.4532016e-08	1.574390e-07
S42401	1.7183668e-07	1.607813e-07
C42402	3.4236733e-08	1.577530e-07
S42402	4.6478368e-08	1.597928e-07
C42403	2.0254288e-07	1.570127e-07
S42403	-2.5518161e-07	1.567779e-07
C42404	-1.0362441e-07	1.569321e-07
S42404	1.4792729e-07	1.549937e-07
C42405	-1.5760621e-07	1.518503e-07
S42405	-1.7922751e-07	1.548083e-07
C42406	1.7824694e-07	1.516605e-07
S42406	8.1839321e-08	1.543569e-07
C42407	-4.2060015e-07	1.464227e-07
S42407	1.8480852e-07	1.508226e-07
C42408	1.5530296e-07	1.466411e-07
S42408	-1.0199483e-08	1.489157e-07
C42409	-1.0799930e-07	1.437728e-07
S42409	1.8782936e-07	1.423060e-07
C42410	-9.0860039e-08	1.400814e-07
S42410	-3.9171734e-07	1.395865e-07
C42411	-3.5993628e-08	1.359835e-07
S42411	1.2999844e-07	1.373819e-07
C42412	-3.2514824e-07	1.338667e-07
S42412	-2.1848529e-07	1.313188e-07
C42413	4.5109331e-08	1.255587e-07
S42413	4.8798197e-08	1.262285e-07
C42414	-6.1852458e-08	1.214508e-07
S42414	3.5466107e-07	1.231192e-07
C42415	1.6501964e-07	1.220011e-07
S42415	-9.3285374e-09	1.226805e-07
C42416	5.2709980e-07	1.180492e-07
S42416	2.6466391e-07	1.219973e-07
C42417	-6.7027745e-08	1.145829e-07
S42417	-1.6402750e-07	1.132405e-07
C42418	2.8099340e-07	1.060135e-07
S42418	-6.4605271e-07	1.123465e-07
C42419	-3.9097042e-07	1.092965e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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S42419	3.7602549e-07	1.076804e-07
C42420	-3.9639484e-08	1.110562e-07
S42420	-3.1820214e-07	1.065062e-07
C42421	1.1803082e-07	1.055218e-07
S42421	4.7038629e-07	1.096369e-07
C42422	-2.0420180e-08	1.002936e-07
S42422	-5.8539474e-07	1.001865e-07
C42423	-5.3543931e-07	8.735188e-08
S42423	1.6245930e-07	8.961685e-08
C42424	4.4934284e-07	7.030090e-08
S42424	1.0160389e-07	6.805069e-08
J425	-2.3700108e-08	1.543891e-07
C42501	-5.0907346e-08	1.546594e-07
S42501	-2.4856660e-07	1.567944e-07
C42502	-6.6282269e-08	1.492610e-07
S42502	-2.5601027e-07	1.498542e-07
C42503	5.8733714e-08	1.532910e-07
S42503	-6.6195631e-08	1.527868e-07
C42504	-3.1021038e-07	1.481192e-07
S42504	-5.6773386e-09	1.457112e-07
C42505	5.5196092e-08	1.477108e-07
S42505	-2.0666396e-07	1.502270e-07
C42506	-1.9890565e-07	1.418547e-07
S42506	3.1233589e-07	1.443540e-07
C42507	6.6840926e-08	1.437796e-07
S42507	2.7515914e-08	1.454439e-07
C42508	3.0902472e-07	1.402400e-07
S42508	1.0284038e-07	1.396445e-07
C42509	-6.1398948e-09	1.406490e-07
S42509	-2.0107597e-08	1.391057e-07
C42510	1.6239923e-07	1.358911e-07
S42510	-8.6936822e-08	1.345315e-07
C42511	-2.8092171e-07	1.321395e-07
S42511	2.1488838e-07	1.323190e-07
C42512	-8.8049893e-08	1.311335e-07
S42512	-1.8081099e-07	1.285468e-07
C42513	1.6856088e-07	1.268412e-07
S42513	3.5186029e-08	1.276971e-07
C42514	3.5371005e-08	1.208103e-07
S42514	9.0492866e-08	1.233282e-07
C42515	2.6085914e-07	1.191165e-07
S42515	-2.3207008e-07	1.178575e-07
C42516	1.5062320e-07	1.171003e-07
S42516	4.4865821e-08	1.201521e-07
C42517	-2.8351099e-07	1.167298e-07
S42517	-7.0830655e-07	1.160057e-07
C42518	5.5136962e-08	1.087733e-07
S42518	-1.0167034e-07	1.149111e-07
C42519	-5.0536446e-07	1.083182e-07
S42519	-6.5375711e-08	1.095565e-07
C42520	3.2145463e-07	1.103812e-07
S42520	5.6784367e-08	1.080236e-07
C42521	-5.4540854e-07	1.059797e-07
S42521	2.6972375e-07	1.082831e-07
C42522	2.1414985e-07	1.049887e-07
S42522	-4.4873934e-07	1.055424e-07
C42523	-3.9100646e-07	9.776471e-08
S42523	4.6677557e-07	9.765414e-08
C42524	4.0304717e-07	8.779613e-08
S42524	-3.1717337e-09	8.773375e-08
C42525	1.1497104e-07	7.114246e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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S42525	-3.8213529e-07	6.898871e-08
J426	1.8309814e-07	1.513409e-07
C42601	-1.1607888e-07	1.482168e-07
S42601	-2.6414621e-07	1.512635e-07
C42602	-1.4076004e-07	1.473878e-07
S42602	-2.9856509e-08	1.491673e-07
C42603	-9.2666116e-08	1.466638e-07
S42603	1.8456783e-07	1.465554e-07
C42604	-3.9605768e-08	1.475241e-07
S42604	1.9522819e-08	1.449800e-07
C42605	2.2773668e-07	1.428606e-07
S42605	1.8042982e-07	1.430334e-07
C42606	-1.7314437e-07	1.404869e-07
S42606	5.2918171e-08	1.423159e-07
C42607	2.8761364e-07	1.387979e-07
S42607	-1.5790417e-07	1.407801e-07
C42608	7.9536403e-08	1.373685e-07
S42608	1.0737676e-07	1.363865e-07
C42609	1.2063411e-07	1.356673e-07
S42609	-3.8383664e-07	1.360776e-07
C42610	1.5924296e-07	1.327317e-07
S42610	1.2049089e-07	1.310428e-07
C42611	-2.3476491e-07	1.300827e-07
S42611	-1.0800806e-07	1.297836e-07
C42612	1.0492204e-07	1.271419e-07
S42612	2.2929581e-09	1.260540e-07
C42613	8.5307553e-09	1.251417e-07
S42613	-5.2199130e-08	1.246600e-07
C42614	1.1517490e-07	1.212569e-07
S42614	-1.4061457e-07	1.229184e-07
C42615	-2.8933302e-09	1.188996e-07
S42615	-3.6456252e-08	1.189076e-07
C42616	-3.0455287e-07	1.162293e-07
S42616	-1.2671347e-07	1.171033e-07
C42617	-5.2080438e-08	1.156164e-07
S42617	-1.7773773e-07	1.155468e-07
C42618	-2.1817326e-07	1.119232e-07
S42618	4.3075685e-07	1.156160e-07
C42619	4.5044624e-08	1.081823e-07
S42619	-1.5265345e-07	1.129281e-07
C42620	2.5620459e-07	1.104829e-07
S42620	3.7556627e-07	1.075780e-07
C42621	-2.9921671e-07	1.081868e-07
S42621	-3.7256552e-07	1.097653e-07
C42622	4.2471069e-07	1.062152e-07
S42622	4.2732842e-08	1.063440e-07
C42623	-1.8727805e-07	1.036859e-07
S42623	2.1007256e-07	1.020466e-07
C42624	5.3564992e-07	9.748605e-08
S42624	-5.5373839e-08	9.622545e-08
C42625	1.7445806e-07	8.802914e-08
S42625	-3.5954877e-07	8.722391e-08
C42626	-2.0712826e-07	6.427754e-08
S42626	4.9098647e-07	7.745387e-08
J427	2.0268702e-07	1.445552e-07
C42701	2.7653624e-08	1.411507e-07
S42701	1.0888206e-08	1.451960e-07
C42702	-9.9768487e-08	1.425890e-07
S42702	1.6576654e-07	1.438232e-07
C42703	-1.7763878e-08	1.419618e-07
S42703	1.5521707e-07	1.407013e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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C42704	2.6979498e-07	1.427857e-07
S42704	-1.2573764e-09	1.413367e-07
C42705	8.7630509e-08	1.385055e-07
S42705	2.2914564e-07	1.393545e-07
C42706	5.3927819e-08	1.382209e-07
S42706	-2.2804237e-07	1.402083e-07
C42707	1.1273631e-07	1.348634e-07
S42707	-1.1918657e-07	1.378441e-07
C42708	-1.0332634e-07	1.363525e-07
S42708	-1.2151685e-07	1.358671e-07
C42709	3.8040245e-08	1.334442e-07
S42709	-2.5807261e-07	1.319573e-07
C42710	-1.4467221e-07	1.317249e-07
S42710	1.0394327e-08	1.308310e-07
C42711	-1.9947450e-07	1.277752e-07
S42711	-1.6839573e-07	1.279731e-07
C42712	7.2559268e-08	1.253149e-07
S42712	1.2951477e-07	1.237917e-07
C42713	-1.5100323e-07	1.227740e-07
S42713	-1.4106251e-07	1.224441e-07
C42714	5.3972501e-08	1.199058e-07
S42714	7.6825714e-08	1.222815e-07
C42715	-1.0727504e-07	1.180371e-07
S42715	5.7402727e-08	1.181348e-07
C42716	-9.6330210e-08	1.151271e-07
S42716	-7.9974656e-08	1.160045e-07
C42717	1.4278409e-07	1.145834e-07
S42717	3.6846206e-07	1.154112e-07
C42718	-8.3959097e-08	1.123245e-07
S42718	1.5660881e-07	1.121432e-07
C42719	4.6662180e-07	1.086225e-07
S42719	1.3330286e-07	1.106853e-07
C42720	-8.2822667e-08	1.083638e-07
S42720	-2.6370160e-08	1.065298e-07
C42721	1.6893671e-07	1.060433e-07
S42721	-2.7774916e-07	1.085972e-07
C42722	6.7275645e-08	1.068717e-07
S42722	3.2014265e-07	1.072248e-07
C42723	4.2977349e-08	1.047526e-07
S42723	-2.7341679e-07	1.028807e-07
C42724	1.2783262e-07	1.028409e-07
S42724	3.4170953e-09	1.002381e-07
C42725	-1.2687569e-07	9.607959e-08
S42725	-4.9663883e-07	9.743523e-08
C42726	-2.4755466e-07	8.610779e-08
S42726	2.7032435e-07	9.096188e-08
C42727	4.3801181e-07	7.583544e-08
S42727	-1.6041534e-07	7.190072e-08
J428	-4.2910375e-08	1.386071e-07
C42801	1.3115409e-07	1.363327e-07
S42801	1.4923856e-07	1.406838e-07
C42802	6.7215211e-08	1.356222e-07
S42802	6.0936750e-08	1.388553e-07
C42803	1.1807237e-07	1.386850e-07
S42803	-7.7952613e-08	1.370158e-07
C42804	1.7596312e-07	1.369229e-07
S42804	-1.1188419e-07	1.357817e-07
C42805	-8.0694998e-08	1.360293e-07
S42805	-8.9402299e-08	1.366462e-07
C42806	1.0511743e-07	1.335018e-07
S42806	-1.8429872e-07	1.357235e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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C42807	-1.6903543e-07	1.328499e-07
S42807	2.2846276e-08	1.344063e-07
C42808	-1.7235463e-07	1.331021e-07
S42808	-1.4647189e-07	1.330469e-07
C42809	-4.7779890e-08	1.323038e-07
S42809	1.5559652e-07	1.305732e-07
C42810	-1.9755935e-07	1.304743e-07
S42810	5.4547831e-08	1.301788e-07
C42811	1.4756205e-07	1.273584e-07
S42811	1.1206598e-07	1.279353e-07
C42812	-1.1978475e-08	1.265410e-07
S42812	1.0769684e-07	1.249615e-07
C42813	3.1017826e-08	1.225222e-07
S42813	5.0619346e-08	1.214772e-07
C42814	2.3194986e-08	1.195229e-07
S42814	1.6103229e-07	1.207213e-07
C42815	-2.9554271e-08	1.184207e-07
S42815	3.5798238e-08	1.184750e-07
C42816	1.7948975e-07	1.164738e-07
S42816	-2.5100508e-09	1.162113e-07
C42817	1.3599265e-07	1.125861e-07
S42817	2.2719298e-07	1.148701e-07
C42818	1.2643371e-07	1.119000e-07
S42818	-2.3415642e-07	1.141345e-07
C42819	2.3072197e-07	1.105196e-07
S42819	3.8653455e-08	1.112040e-07
C42820	-1.2673421e-07	1.086723e-07
S42820	-3.6997617e-07	1.074968e-07
C42821	1.6161465e-07	1.058124e-07
S42821	-1.0879176e-08	1.054861e-07
C42822	-2.6490497e-07	1.056683e-07
S42822	-2.5952168e-08	1.057660e-07
C42823	3.4476248e-07	1.068436e-07
S42823	-6.7047852e-08	1.048345e-07
C42824	-2.3566239e-07	1.057032e-07
S42824	4.7852830e-08	1.022814e-07
C42825	1.5511582e-08	1.013780e-07
S42825	-2.8835071e-07	1.040354e-07
C42826	-2.1891864e-07	9.761932e-08
S42826	5.2200699e-07	1.005180e-07
C42827	2.6038248e-07	9.273397e-08
S42827	-4.4267234e-09	8.961260e-08
C42828	-3.2359595e-07	7.754509e-08
S42828	-3.3548875e-07	7.623784e-08
J429	-7.3178556e-08	1.360691e-07
C42901	-2.9298208e-08	1.334651e-07
S42901	6.5704926e-08	1.386260e-07
C42902	5.1313838e-08	1.327578e-07
S42902	-9.1949273e-08	1.371195e-07
C42903	-1.5658414e-08	1.368425e-07
S42903	-1.6908057e-07	1.337468e-07
C42904	-1.0436422e-07	1.349201e-07
S42904	-3.5780350e-08	1.329262e-07
C42905	-1.7025661e-07	1.340571e-07
S42905	-1.4316558e-07	1.341353e-07
C42906	-4.3299718e-08	1.306979e-07
S42906	4.2084825e-08	1.335280e-07
C42907	-1.6155228e-07	1.319700e-07
S42907	1.1129924e-07	1.328895e-07
C42908	-1.2306633e-08	1.303150e-07
S42908	1.1905758e-07	1.295495e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
C42909	-1.5802162e-08	1.309582e-07
S42909	2.1105097e-07	1.299368e-07
C42910	7.6136397e-08	1.279966e-07
S42910	5.7234043e-08	1.271307e-07
C42911	2.0710170e-07	1.271200e-07
S42911	3.8287040e-08	1.275627e-07
C42912	-1.7342253e-08	1.258892e-07
S42912	-5.5149655e-08	1.248003e-07
C42913	1.5179939e-07	1.234120e-07
S42913	6.2333414e-08	1.226010e-07
C42914	3.2537518e-08	1.190980e-07
S42914	-6.3107336e-08	1.213590e-07
C42915	2.5959177e-08	1.184081e-07
S42915	-3.5770731e-09	1.188655e-07
C42916	5.6112719e-08	1.169593e-07
S42916	2.6834740e-08	1.165668e-07
C42917	3.5512220e-09	1.153643e-07
S42917	-7.8263079e-08	1.145294e-07
C42918	1.4642941e-08	1.133702e-07
S42918	-2.0588399e-07	1.135048e-07
C42919	-2.4391518e-07	1.122375e-07
S42919	-9.2251284e-08	1.125596e-07
C42920	-5.9248058e-08	1.101109e-07
S42920	-2.0482823e-07	1.105625e-07
C42921	-1.1094408e-07	1.065593e-07
S42921	1.7242123e-07	1.096514e-07
C42922	-9.5984644e-08	1.066604e-07
S42922	-4.2755257e-08	1.066184e-07
C42923	1.2320924e-07	1.088230e-07
S42923	2.2784906e-07	1.052878e-07
C42924	-9.1882190e-08	1.088339e-07
S42924	-1.2106983e-07	1.061839e-07
C42925	2.1818088e-07	1.036737e-07
S42925	2.2979936e-07	1.067847e-07
C42926	-9.5737160e-08	1.028989e-07
S42926	1.4130160e-07	1.050849e-07
C42927	3.5607314e-07	1.013388e-07
S42927	-5.9770877e-08	9.915876e-08
C42928	2.6386215e-08	9.179516e-08
S42928	-1.4596725e-07	9.357260e-08
C42929	-1.8485613e-07	7.881804e-08
S42929	2.7586892e-07	8.071365e-08
J430	-3.8569462e-08	1.341032e-07
C43001	-5.9868199e-08	1.305650e-07
S43001	-7.1345332e-08	1.357101e-07
C43002	-2.4621837e-08	1.310451e-07
S43002	-1.2132963e-08	1.354196e-07
C43003	-6.7661568e-08	1.335170e-07
S43003	1.2959909e-08	1.309605e-07
C43004	-1.5701556e-07	1.325446e-07
S43004	3.5287051e-08	1.322409e-07
C43005	-4.5374258e-08	1.308441e-07
S43005	4.3654722e-08	1.304735e-07
C43006	-2.1475232e-08	1.302975e-07
S43006	1.5316470e-07	1.315327e-07
C43007	2.7049579e-08	1.286194e-07
S43007	5.2116003e-08	1.300446e-07
C43008	1.8699305e-07	1.292799e-07
S43008	1.1321938e-07	1.285125e-07
C43009	1.9082961e-08	1.279525e-07
S43009	7.4819997e-09	1.266927e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
C43010	1.5142462e-07	1.266781e-07
S43010	-1.4984888e-07	1.263455e-07
C43011	-5.0645266e-08	1.242192e-07
S43011	-5.1147806e-08	1.255754e-07
C43012	-4.7224567e-08	1.240419e-07
S43012	-1.2646304e-07	1.236770e-07
C43013	-6.8662082e-08	1.232673e-07
S43013	-3.0129030e-08	1.210777e-07
C43014	-6.4492860e-08	1.196116e-07
S43014	-1.0344260e-07	1.204769e-07
C43015	1.9825970e-08	1.178334e-07
S43015	1.4281362e-08	1.184566e-07
C43016	9.5421132e-09	1.170867e-07
S43016	-1.2842519e-08	1.167146e-07
C43017	-7.4057122e-08	1.140591e-07
S43017	1.6064488e-10	1.159725e-07
C43018	-6.3218286e-08	1.139118e-07
S43018	1.6725529e-08	1.125760e-07
C43019	-2.1880755e-07	1.127439e-07
S43019	9.5665188e-08	1.116710e-07
C43020	6.6905442e-08	1.119692e-07
S43020	1.7668084e-07	1.108512e-07
C43021	-6.6033794e-08	1.086660e-07
S43021	1.0881687e-07	1.108394e-07
C43022	1.8189366e-07	1.087385e-07
S43022	1.8620951e-08	1.072281e-07
C43023	-2.0399201e-08	1.080104e-07
S43023	1.5263170e-07	1.068106e-07
C43024	1.0069693e-07	1.089089e-07
S43024	-1.1971787e-07	1.079271e-07
C43025	-6.2732674e-09	1.070457e-07
S43025	1.7796956e-07	1.100308e-07
C43026	4.7013404e-08	1.062088e-07
S43026	-3.8236606e-07	1.056326e-07
C43027	1.3655672e-07	1.063793e-07
S43027	-8.8174168e-08	1.029710e-07
C43028	-2.2976804e-07	1.018533e-07
S43028	-2.1666676e-07	1.008875e-07
C43029	-6.9373434e-08	9.496730e-08
S43029	-1.0451594e-08	9.325290e-08
C43030	2.6730835e-07	7.911255e-08
S43030	-1.0768167e-07	8.498813e-08
J431	4.4923665e-09	1.328332e-07
C43101	-5.0419357e-08	1.278961e-07
S43101	-2.6984250e-08	1.331480e-07
C43102	-3.6690288e-08	1.284134e-07
S43102	3.7516582e-08	1.343341e-07
C43103	-1.6790485e-08	1.315507e-07
S43103	1.4900241e-07	1.281894e-07
C43104	-9.4195291e-09	1.311351e-07
S43104	5.2326663e-08	1.296360e-07
C43105	1.5168243e-07	1.286043e-07
S43105	4.3781202e-08	1.285168e-07
C43106	4.3968612e-08	1.277910e-07
S43106	4.7241537e-08	1.300378e-07
C43107	1.7991440e-07	1.255201e-07
S43107	-6.5807867e-08	1.275478e-07
C43108	4.6428876e-08	1.277392e-07
S43108	-7.3525636e-08	1.269654e-07
C43109	2.2528578e-08	1.254303e-07
S43109	-1.0889930e-07	1.240505e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
C43110	-8.6788832e-08	1.250348e-07
S43110	-5.1704916e-08	1.249988e-07
C43111	-6.5769533e-08	1.228316e-07
S43111	9.8264295e-09	1.232027e-07
C43112	-1.0688633e-07	1.223401e-07
S43112	1.8288457e-08	1.218053e-07
C43113	-7.7369699e-08	1.217110e-07
S43113	9.7874876e-08	1.206124e-07
C43114	-7.7906043e-08	1.185809e-07
S43114	4.3512420e-08	1.199498e-07
C43115	1.5668109e-08	1.172191e-07
S43115	-2.8679848e-09	1.178350e-07
C43116	-6.4246031e-08	1.167454e-07
S43116	3.6274410e-08	1.152740e-07
C43117	-1.5612518e-08	1.155516e-07
S43117	9.4691081e-08	1.142034e-07
C43118	6.0647870e-08	1.125221e-07
S43118	3.8968296e-08	1.137968e-07
C43119	3.4673838e-08	1.119628e-07
S43119	1.0878582e-07	1.117306e-07
C43120	1.9506567e-07	1.108820e-07
S43120	1.3067161e-07	1.114118e-07
C43121	1.2525190e-07	1.095919e-07
S43121	-3.8537351e-08	1.104260e-07
C43122	7.8879260e-08	1.104795e-07
S43122	-4.3865354e-08	1.074042e-07
C43123	-3.9632108e-08	1.082730e-07
S43123	-1.0014516e-07	1.072579e-07
C43124	7.4695422e-08	1.082751e-07
S43124	3.3113684e-08	1.075070e-07
C43125	-1.5917173e-07	1.064981e-07
S43125	-2.5933728e-08	1.117530e-07
C43126	1.1819673e-07	1.095554e-07
S43126	-1.6990444e-07	1.078322e-07
C43127	-7.0678511e-08	1.081810e-07
S43127	-8.2521804e-08	1.043218e-07
C43128	-8.5849546e-08	1.054078e-07
S43128	-1.0177887e-07	1.043202e-07
C43129	-2.1430153e-08	1.019001e-07
S43129	1.9104310e-07	1.020186e-07
C43130	-1.1774605e-07	9.330168e-08
S43130	1.1980372e-07	9.731405e-08
C43131	-1.0749071e-07	8.467105e-08
S43131	6.3234629e-08	8.337005e-08
J432	9.9407025e-09	1.290178e-07
C43201	3.5810268e-09	1.272134e-07
S43201	5.4553280e-09	1.331372e-07
C43202	8.5349539e-08	1.247872e-07
S43202	1.4592889e-08	1.301458e-07
C43203	1.7176635e-08	1.321286e-07
S43203	3.8716451e-08	1.274245e-07
C43204	1.2703277e-07	1.268767e-07
S43204	-9.6219464e-08	1.265684e-07
C43205	8.6926011e-08	1.286245e-07
S43205	-1.6725829e-12	1.287845e-07
C43206	-4.0681053e-08	1.247903e-07
S43206	-1.8552913e-07	1.262195e-07
C43207	8.5403427e-08	1.262359e-07
S43207	-6.2008221e-08	1.272481e-07
C43208	-1.9924093e-07	1.246914e-07
S43208	-3.0784652e-08	1.238562e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
C43209	-5.8639228e-09	1.254458e-07
S43209	-9.2327191e-08	1.237174e-07
C43210	-8.5931655e-08	1.221908e-07
S43210	9.7275851e-08	1.224922e-07
C43211	-7.0339557e-08	1.211078e-07
S43211	1.0063142e-08	1.228237e-07
C43212	1.0827801e-08	1.209001e-07
S43212	8.2074531e-08	1.206555e-07
C43213	1.0398825e-07	1.209978e-07
S43213	7.7983034e-08	1.181471e-07
C43214	7.9560319e-08	1.180814e-07
S43214	3.6953770e-08	1.192472e-07
C43215	5.9975323e-08	1.161054e-07
S43215	-4.8649785e-08	1.179790e-07
C43216	-8.5482416e-08	1.156076e-07
S43216	9.3197605e-09	1.155484e-07
C43217	7.7208427e-08	1.138273e-07
S43217	7.1863501e-09	1.147232e-07
C43218	1.1678455e-08	1.139136e-07
S43218	-3.0191899e-08	1.125226e-07
C43219	9.1249247e-08	1.120768e-07
S43219	-8.9204472e-08	1.111672e-07
C43220	5.9194746e-08	1.106290e-07
S43220	-3.1539613e-08	1.108305e-07
C43221	6.2411436e-08	1.086251e-07
S43221	-1.3728519e-07	1.110909e-07
C43222	-1.1898999e-07	1.099364e-07
S43222	-7.0841876e-08	1.070551e-07
C43223	-6.4054212e-08	1.093770e-07
S43223	1.9630995e-08	1.067753e-07
C43224	-1.1545622e-07	1.076059e-07
S43224	8.1033109e-08	1.074136e-07
C43225	-8.8476727e-10	1.063928e-07
S43225	-5.2477017e-08	1.100206e-07
C43226	-1.8452317e-08	1.107334e-07
S43226	7.8385159e-10	1.082303e-07
C43227	-2.8363074e-08	1.100821e-07
S43227	-3.6288110e-09	1.070837e-07
C43228	1.4412590e-08	1.060616e-07
S43228	1.5930019e-07	1.063589e-07
C43229	1.2017040e-07	1.042576e-07
S43229	1.3166134e-07	1.055995e-07
C43230	-1.7722441e-08	1.015232e-07
S43230	-8.9683337e-08	1.029699e-07
C43231	1.5599682e-07	9.725922e-08
S43231	6.0268942e-08	9.527401e-08
C43232	4.0475922e-08	8.498155e-08
S43232	2.0204610e-08	8.717424e-08
J433	3.3301648e-08	1.280607e-07
C43301	3.2050145e-08	1.235484e-07
S43301	-8.0248566e-08	1.291338e-07
C43302	2.6743153e-08	1.232574e-07
S43302	3.4521254e-08	1.307493e-07
C43303	-1.1119493e-08	1.277646e-07
S43303	-6.8385572e-08	1.237017e-07
C43304	7.7447723e-08	1.267254e-07
S43304	-5.0017265e-08	1.262365e-07
C43305	-9.1720007e-08	1.253746e-07
S43305	3.9509732e-08	1.241412e-07
C43306	-6.4483317e-08	1.245817e-07
S43306	-1.1425136e-07	1.260815e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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C43307	-1.1082710e-07	1.223821e-07
S43307	1.1230808e-07	1.243775e-07
C43308	-4.2773623e-08	1.240951e-07
S43308	-1.1834917e-08	1.231408e-07
C43309	2.9190716e-08	1.229712e-07
S43309	5.5791519e-08	1.217313e-07
C43310	-2.3290470e-09	1.212007e-07
S43310	4.3625601e-08	1.216282e-07
C43311	6.2124236e-08	1.199049e-07
S43311	2.1679055e-09	1.209525e-07
C43312	1.0336317e-07	1.197561e-07
S43312	-5.7062977e-09	1.194744e-07
C43313	3.8806655e-08	1.194321e-07
S43313	-1.2955168e-07	1.174675e-07
C43314	5.7341687e-08	1.171240e-07
S43314	-9.8344724e-09	1.179891e-07
C43315	-3.6575305e-08	1.159290e-07
S43315	-2.4470573e-08	1.166659e-07
C43316	3.2568100e-08	1.160503e-07
S43316	-6.5314698e-08	1.138107e-07
C43317	1.3575138e-08	1.144568e-07
S43317	1.2270020e-08	1.131341e-07
C43318	-9.6763919e-08	1.125673e-07
S43318	-4.0734462e-08	1.125285e-07
C43319	5.7613358e-09	1.107445e-07
S43319	-7.3345094e-08	1.122021e-07
C43320	-8.9310573e-08	1.097278e-07
S43320	-3.2588387e-08	1.104245e-07
C43321	-4.3750815e-08	1.090910e-07
S43321	-9.1728673e-08	1.096728e-07
C43322	-8.6268864e-08	1.090477e-07
S43322	1.5954404e-08	1.075055e-07
C43323	-6.6663131e-08	1.078411e-07
S43323	1.0276757e-07	1.068742e-07
C43324	3.2243024e-08	1.063558e-07
S43324	1.0386740e-07	1.082177e-07
C43325	4.9641235e-08	1.060701e-07
S43325	-3.0916326e-10	1.082371e-07
C43326	2.0629596e-08	1.092984e-07
S43326	-5.2199169e-08	1.070252e-07
C43327	1.7241091e-07	1.112680e-07
S43327	5.7065594e-08	1.070486e-07
C43328	2.6691717e-08	1.065076e-07
S43328	2.7266436e-08	1.096038e-07
C43329	1.5804015e-07	1.061720e-07
S43329	-3.1926180e-09	1.052917e-07
C43330	1.0905304e-08	1.036057e-07
S43330	-2.4364993e-07	1.060015e-07
C43331	-1.7421680e-07	1.036440e-07
S43331	-7.5248970e-08	1.012635e-07
C43332	1.6209768e-07	9.665506e-08
S43332	-2.1808918e-07	9.795905e-08
C43333	6.5012110e-08	8.917270e-08
S43333	-2.1251252e-07	8.652815e-08
J434	5.9773889e-08	1.249232e-07
C43401	2.1520188e-08	1.208259e-07
S43401	-2.0887175e-08	1.278091e-07
C43402	-1.0139432e-07	1.201321e-07
S43402	1.9053828e-08	1.278778e-07
C43403	1.4968869e-08	1.269169e-07
S43403	-9.0883477e-08	1.205447e-07
C43404	-4.6061882e-08	1.238898e-07
S43404	8.5535383e-08	1.231431e-07
C43405	-9.3133955e-08	1.228923e-07
S43405	-4.1685462e-08	1.233147e-07
C43406	6.0552280e-08	1.214349e-07
S43406	9.9163309e-08	1.237569e-07
C43407	-5.1462791e-08	1.207809e-07
S43407	9.0604067e-08	1.226883e-07
C43408	1.0136131e-07	1.222938e-07
S43408	-4.4408451e-08	1.201445e-07
C43409	8.2207142e-08	1.216712e-07
S43409	9.7959722e-08	1.193319e-07
C43410	1.5832890e-08	1.189046e-07
S43410	-5.5139848e-08	1.199024e-07
C43411	1.2402620e-07	1.181785e-07
S43411	-5.6977678e-08	1.199658e-07
C43412	3.3427622e-10	1.178503e-07
S43412	-6.4389970e-08	1.171114e-07
C43413	-6.1624767e-08	1.190456e-07
S43413	-1.0520927e-07	1.163463e-07
C43414	-3.4997422e-08	1.155946e-07
S43414	5.0626730e-08	1.166331e-07
C43415	-1.3817470e-07	1.139221e-07
S43415	1.0306990e-08	1.172410e-07
C43416	4.9055115e-08	1.140172e-07
S43416	-3.8324398e-08	1.144120e-07
C43417	-8.4253022e-08	1.132207e-07
S43417	5.8755548e-08	1.123691e-07
C43418	6.2922277e-09	1.119471e-07
S43418	-3.7397858e-08	1.121518e-07
C43419	-2.8744674e-08	1.108939e-07
S43419	1.0990715e-07	1.104847e-07
C43420	-2.2598359e-08	1.100395e-07
S43420	-3.6010378e-08	1.098847e-07
C43421	3.3501062e-08	1.077303e-07
S43421	1.0825857e-07	1.093386e-07
C43422	3.0224983e-08	1.085202e-07
S43422	4.3442414e-08	1.076509e-07
C43423	-9.5782757e-09	1.074700e-07
S43423	6.9154988e-09	1.060991e-07
C43424	1.2747257e-07	1.052133e-07
S43424	-1.3518770e-08	1.074544e-07
C43425	-3.4903195e-08	1.046873e-07
S43425	-5.6879205e-08	1.086869e-07
C43426	9.1968354e-08	1.075771e-07
S43426	-1.5241900e-07	1.054987e-07
C43427	3.0081330e-08	1.103639e-07
S43427	4.6612999e-08	1.053342e-07
C43428	7.4111876e-08	1.074050e-07
S43428	-1.1383865e-07	1.097485e-07
C43429	2.4670176e-08	1.080072e-07
S43429	6.5232406e-08	1.068242e-07
C43430	-3.9370994e-08	1.053416e-07
S43430	-1.3965898e-07	1.052585e-07
C43431	-1.7106932e-07	1.056412e-07
S43431	-3.1748954e-08	1.033188e-07
C43432	1.6503595e-07	1.017548e-07
S43432	5.6420319e-08	1.035203e-07
C43433	-3.2124851e-07	9.834875e-08
S43433	3.8627337e-08	9.783539e-08
C43434	2.5420543e-08	9.052163e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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S43434	8.7967443e-08	8.836712e-08
J435	4.2673215e-09	1.222710e-07
C43501	6.0350972e-09	1.190467e-07
S43501	1.1572754e-07	1.249002e-07
C43502	-6.1348156e-08	1.176960e-07
S43502	-5.4566073e-08	1.249573e-07
C43503	7.8208920e-08	1.240793e-07
S43503	1.7533286e-08	1.192465e-07
C43504	-7.5334893e-08	1.205028e-07
S43504	6.0542806e-08	1.212527e-07
C43505	9.0185177e-08	1.216362e-07
S43505	-4.3080342e-08	1.200634e-07
C43506	4.3519451e-08	1.201258e-07
S43506	1.1668387e-07	1.205487e-07
C43507	1.7701766e-08	1.181783e-07
S43507	-1.4670323e-07	1.209361e-07
C43508	8.8034761e-08	1.198459e-07
S43508	2.3657894e-08	1.192504e-07
C43509	-8.6256471e-08	1.191089e-07
S43509	-8.4792898e-08	1.170742e-07
C43510	7.2581491e-08	1.178044e-07
S43510	-1.0064740e-07	1.191813e-07
C43511	-1.1652567e-07	1.154292e-07
S43511	5.3614166e-09	1.171597e-07
C43512	-8.9220930e-08	1.173249e-07
S43512	-6.2024414e-08	1.164731e-07
C43513	-1.7877176e-08	1.158371e-07
S43513	5.8070245e-08	1.137290e-07
C43514	-3.8348582e-08	1.149468e-07
S43514	8.3430179e-08	1.156700e-07
C43515	3.1644885e-08	1.134505e-07
S43515	3.7695053e-08	1.141666e-07
C43516	2.3008055e-08	1.142201e-07
S43516	3.9761327e-08	1.123902e-07
C43517	-4.8172371e-08	1.129141e-07
S43517	-5.2334452e-08	1.115223e-07
C43518	1.0430195e-07	1.105050e-07
S43518	7.9011871e-09	1.109271e-07
C43519	-1.4358277e-08	1.088736e-07
S43519	5.2945696e-08	1.117257e-07
C43520	6.2371356e-08	1.080503e-07
S43520	-5.7291973e-08	1.094518e-07
C43521	7.4659718e-08	1.082215e-07
S43521	1.0741789e-07	1.082808e-07
C43522	3.4969114e-08	1.082144e-07
S43522	-7.3990014e-08	1.055872e-07
C43523	3.5401435e-08	1.079992e-07
S43523	3.1270455e-08	1.050917e-07
C43524	-4.1989871e-08	1.048459e-07
S43524	-4.1608744e-08	1.060334e-07
C43525	-2.6918891e-10	1.049020e-07
S43525	-8.8382445e-08	1.060225e-07
C43526	8.9191176e-09	1.065744e-07
S43526	8.1885230e-09	1.056064e-07
C43527	-1.1681272e-07	1.061607e-07
S43527	-8.2254131e-08	1.056293e-07
C43528	1.2491258e-07	1.055021e-07
S43528	1.2692504e-08	1.092005e-07
C43529	-1.2049448e-07	1.071494e-07
S43529	6.5973800e-09	1.087245e-07
C43530	8.7941148e-08	1.080509e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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S43530	1.8358854e-08	1.050338e-07
C43531	-6.4990545e-08	1.045261e-07
S43531	5.5733707e-09	1.047547e-07
C43532	1.5985830e-07	1.038917e-07
S43532	1.4465680e-07	1.037635e-07
C43533	-1.3377561e-07	1.022293e-07
S43533	-2.3367640e-07	1.030467e-07
C43534	2.4106788e-07	1.001584e-07
S43534	2.5161575e-07	9.744905e-08
C43535	1.4322595e-07	9.068395e-08
S43535	2.0527501e-07	9.116575e-08
J436	-1.3200477e-07	1.201854e-07
C43601	-3.3228878e-08	1.160554e-07
S43601	2.4985986e-08	1.229150e-07
C43602	8.5205157e-08	1.147267e-07
S43602	-1.0480651e-07	1.237318e-07
C43603	4.5574666e-09	1.224031e-07
S43603	1.0049446e-07	1.160342e-07
C43604	-5.8068871e-08	1.194863e-07
S43604	-1.0812578e-07	1.179730e-07
C43605	1.1650452e-07	1.190147e-07
S43605	3.2647207e-08	1.183309e-07
C43606	-9.0477046e-08	1.162211e-07
S43606	-9.1186190e-09	1.192378e-07
C43607	6.9122228e-08	1.170097e-07
S43607	-9.8272535e-08	1.189619e-07
C43608	-2.3905313e-08	1.179375e-07
S43608	4.5740261e-08	1.149179e-07
C43609	-9.7463771e-08	1.179751e-07
S43609	-7.4816084e-08	1.161120e-07
C43610	-1.1470222e-09	1.142910e-07
S43610	2.9379932e-08	1.160230e-07
C43611	-8.8357778e-08	1.150298e-07
S43611	7.1027034e-08	1.162931e-07
C43612	-1.0477938e-08	1.144618e-07
S43612	2.1970670e-08	1.132414e-07
C43613	6.6155880e-09	1.149825e-07
S43613	9.2055819e-08	1.128499e-07
C43614	-1.5105008e-08	1.118468e-07
S43614	-1.2624336e-08	1.131260e-07
C43615	1.4268154e-07	1.109584e-07
S43615	2.4584768e-08	1.140659e-07
C43616	-2.5879451e-08	1.114096e-07
S43616	3.2631660e-08	1.114014e-07
C43617	1.5143240e-08	1.114307e-07
S43617	-8.8197619e-08	1.099876e-07
C43618	1.6211605e-08	1.104614e-07
S43618	5.2648433e-08	1.097038e-07
C43619	-2.8566661e-08	1.085660e-07
S43619	-8.8589570e-08	1.085120e-07
C43620	3.5843859e-08	1.098114e-07
S43620	5.3828799e-08	1.073792e-07
C43621	-8.4358604e-09	1.060402e-07
S43621	-4.5127674e-08	1.073758e-07
C43622	4.7426150e-10	1.057855e-07
S43622	-1.5133117e-08	1.072299e-07
C43623	1.3099844e-09	1.056886e-07
S43623	1.6533432e-08	1.050284e-07
C43624	-6.7469213e-08	1.042952e-07
S43624	-2.4009994e-08	1.056065e-07
C43625	5.8302536e-08	1.031531e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
S43625	-2.6464268e-08	1.051328e-07
C43626	-7.1594209e-08	1.060455e-07
S43626	4.7945952e-08	1.026056e-07
C43627	4.1300362e-08	1.071258e-07
S43627	-3.5664329e-08	1.033600e-07
C43628	1.0147693e-08	1.044652e-07
S43628	1.0628204e-07	1.055431e-07
C43629	-4.0221973e-08	1.053625e-07
S43629	-8.1830595e-08	1.079402e-07
C43630	7.4853365e-08	1.075269e-07
S43630	1.9703886e-07	1.060508e-07
C43631	-3.1767452e-08	1.045855e-07
S43631	-9.4927645e-08	1.063127e-07
C43632	1.2704652e-07	1.036019e-07
S43632	1.2784280e-07	1.041283e-07
C43633	-2.6631605e-08	1.029799e-07
S43633	-2.5165837e-07	1.036806e-07
C43634	3.3748557e-08	1.041513e-07
S43634	1.3970594e-07	1.007856e-07
C43635	1.7152619e-07	1.005287e-07
S43635	-1.5500829e-07	9.798517e-08
C43636	-3.2468407e-09	9.222062e-08
S43636	-1.1539612e-07	9.208664e-08
J437	-1.5598900e-08	1.175036e-07
C43701	-8.2675807e-08	1.138149e-07
S43701	-9.6181420e-08	1.205086e-07
C43702	6.8827064e-08	1.127354e-07
S43702	1.3148346e-08	1.207608e-07
C43703	-1.6349956e-07	1.194000e-07
S43703	-5.4537561e-10	1.138290e-07
C43704	5.0997049e-08	1.162255e-07
S43704	-7.1306677e-08	1.167630e-07
C43705	-7.3079347e-08	1.166870e-07
S43705	7.6665875e-08	1.153662e-07
C43706	-2.8661380e-08	1.156615e-07
S43706	-1.1823145e-07	1.160215e-07
C43707	3.6309049e-08	1.141606e-07
S43707	8.1525533e-08	1.163908e-07
C43708	-1.4753488e-07	1.155756e-07
S43708	-7.4590279e-09	1.143336e-07
C43709	7.7529725e-08	1.150423e-07
S43709	5.5915760e-08	1.132571e-07
C43710	-6.9924058e-08	1.128801e-07
S43710	1.3982908e-07	1.147124e-07
C43711	8.7704920e-08	1.118939e-07
S43711	-4.6237146e-09	1.138112e-07
C43712	7.6459539e-08	1.131290e-07
S43712	7.7491457e-08	1.116213e-07
C43713	-1.3392399e-09	1.126964e-07
S43713	2.9120311e-08	1.104219e-07
C43714	3.0328116e-08	1.104987e-07
S43714	-7.0871576e-08	1.117376e-07
C43715	3.7094099e-08	1.092237e-07
S43715	-1.3569060e-08	1.110479e-07
C43716	-4.0544449e-08	1.107412e-07
S43716	-2.3552821e-08	1.093587e-07
C43717	1.9312888e-08	1.100106e-07
S43717	2.0186974e-08	1.080079e-07
C43718	-6.3238017e-08	1.077555e-07
S43718	-3.9308887e-09	1.090858e-07
C43719	3.3730326e-08	1.062110e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
S43719	-1.9184891e-08	1.097283e-07
C43720	-1.9682981e-08	1.058152e-07
S43720	1.0441641e-07	1.072707e-07
C43721	-2.1716506e-08	1.068865e-07
S43721	-7.6620110e-08	1.066645e-07
C43722	6.2558655e-08	1.059714e-07
S43722	1.0943350e-07	1.036181e-07
C43723	-4.8031278e-08	1.058356e-07
S43723	-8.6925673e-08	1.035856e-07
C43724	1.0467682e-08	1.025432e-07
S43724	-1.0824166e-08	1.049375e-07
C43725	-2.4354560e-08	1.024584e-07
S43725	2.2356741e-08	1.038124e-07
C43726	1.9378814e-08	1.031045e-07
S43726	-4.1619233e-08	1.028616e-07
C43727	1.2695600e-07	1.032345e-07
S43727	2.9717719e-08	1.029551e-07
C43728	-6.3499639e-08	1.041134e-07
S43728	4.3157555e-08	1.043397e-07
C43729	9.3515111e-08	1.040596e-07
S43729	-5.5124779e-08	1.037668e-07
C43730	-1.1921764e-07	1.067521e-07
S43730	1.2608383e-07	1.040724e-07
C43731	6.5666273e-08	1.066379e-07
S43731	-9.7324020e-08	1.040917e-07
C43732	-9.9124078e-08	1.024143e-07
S43732	1.1187522e-07	1.059611e-07
C43733	3.6062943e-08	1.034067e-07
S43733	-1.7679506e-07	1.022540e-07
C43734	-6.6565930e-08	1.029027e-07
S43734	3.1537327e-08	1.022170e-07
C43735	1.3903344e-07	1.029715e-07
S43735	-3.4760587e-09	1.016017e-07
C43736	-2.6364762e-07	9.797176e-08
S43736	3.4867987e-08	1.008134e-07
C43737	-1.8848801e-08	9.240224e-08
S43737	1.1908815e-07	9.345511e-08
J438	1.0162794e-07	1.149362e-07
C43801	-1.0418005e-08	1.111193e-07
S43801	-5.4734783e-08	1.171546e-07
C43802	-4.7623457e-08	1.101096e-07
S43802	1.4203346e-07	1.180482e-07
C43803	-3.4011196e-08	1.165835e-07
S43803	-5.3690011e-08	1.112204e-07
C43804	9.2379190e-08	1.138733e-07
S43804	1.2680031e-07	1.137925e-07
C43805	-1.1207305e-07	1.141550e-07
S43805	-8.7369263e-09	1.126399e-07
C43806	9.7754517e-08	1.121430e-07
S43806	-1.3708192e-08	1.145178e-07
C43807	-5.0070908e-08	1.108949e-07
S43807	8.6541484e-08	1.142814e-07
C43808	2.5352717e-08	1.139018e-07
S43808	-2.0823970e-08	1.115728e-07
C43809	4.8211443e-08	1.128469e-07
S43809	7.2286769e-08	1.104529e-07
C43810	2.4759028e-08	1.107663e-07
S43810	-1.4416613e-08	1.128182e-07
C43811	5.4013519e-08	1.102490e-07
S43811	-3.3758566e-08	1.110557e-07
C43812	1.9209971e-08	1.111662e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
S43812	-5.3601218e-09	1.094533e-07
C43813	1.8088895e-08	1.100989e-07
S43813	-2.7448522e-08	1.090532e-07
C43814	1.5085556e-08	1.083474e-07
S43814	-1.7973855e-08	1.096715e-07
C43815	-4.6942946e-08	1.077689e-07
S43815	-2.6926716e-08	1.088895e-07
C43816	2.2855420e-08	1.078363e-07
S43816	1.1450778e-08	1.079207e-07
C43817	1.1224743e-08	1.080667e-07
S43817	6.0241997e-08	1.067503e-07
C43818	-2.7679812e-09	1.071605e-07
S43818	-2.9671687e-08	1.065326e-07
C43819	6.4715782e-08	1.059073e-07
S43819	7.3164435e-10	1.064032e-07
C43820	-1.3541272e-08	1.073728e-07
S43820	-1.2808865e-08	1.043140e-07
C43821	1.9173540e-08	1.041507e-07
S43821	-1.4052042e-08	1.047909e-07
C43822	6.1796790e-09	1.038894e-07
S43822	-2.8296101e-08	1.054989e-07
C43823	-6.2910513e-08	1.033145e-07
S43823	-3.8543842e-08	1.019905e-07
C43824	1.1834503e-08	1.030819e-07
S43824	4.4812096e-08	1.022575e-07
C43825	-6.5955366e-08	1.010803e-07
S43825	2.0663661e-08	1.029119e-07
C43826	6.7396305e-08	1.016189e-07
S43826	-8.1970849e-08	1.008833e-07
C43827	8.2634314e-10	1.026548e-07
S43827	2.7180199e-08	1.006793e-07
C43828	1.4260582e-08	1.013338e-07
S43828	-9.1306927e-08	1.022257e-07
C43829	6.5961326e-08	1.014666e-07
S43829	1.2876930e-07	1.045787e-07
C43830	-1.7488686e-07	1.029746e-07
S43830	-4.4494567e-08	1.023920e-07
C43831	1.6273468e-07	1.055061e-07
S43831	3.2081148e-08	1.028613e-07
C43832	-1.9195452e-07	1.023956e-07
S43832	1.4442405e-08	1.054549e-07
C43833	1.6192609e-07	1.045013e-07
S43833	-8.6592928e-08	1.014842e-07
C43834	-3.4120720e-08	1.016413e-07
S43834	2.5683506e-08	1.020797e-07
C43835	1.0898408e-07	1.023913e-07
S43835	5.8810740e-08	1.013035e-07
C43836	-1.3940899e-07	1.000163e-07
S43836	-9.9209664e-08	1.038581e-07
C43837	1.5498178e-07	9.862026e-08
S43837	3.3994490e-07	9.985437e-08
C43838	1.7734736e-07	9.167137e-08
S43838	1.2844420e-08	9.509776e-08
J439	4.1124152e-08	1.120217e-07
C43901	9.7257291e-08	1.083241e-07
S43901	1.1046801e-07	1.151602e-07
C43902	-5.3452724e-08	1.067147e-07
S43902	1.6949170e-08	1.153155e-07
C43903	1.3879970e-07	1.143395e-07
S43903	-1.1748799e-08	1.085149e-07
C43904	-2.3686240e-08	1.111534e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
S43904	7.2468817e-08	1.104383e-07
C43905	3.8858799e-08	1.118480e-07
S43905	-1.0668441e-07	1.102540e-07
C43906	5.0648510e-08	1.094677e-07
S43906	7.2670457e-08	1.109616e-07
C43907	-5.7387013e-08	1.097938e-07
S43907	-3.2979138e-08	1.111993e-07
C43908	1.2716386e-07	1.107119e-07
S43908	1.6979870e-09	1.085265e-07
C43909	-3.1502304e-08	1.103108e-07
S43909	2.9603065e-09	1.092318e-07
C43910	3.3295343e-08	1.076290e-07
S43910	-8.7603729e-08	1.099222e-07
C43911	4.3557265e-09	1.081386e-07
S43911	5.7512791e-09	1.094157e-07
C43912	-1.1305757e-08	1.085591e-07
S43912	-4.6224215e-08	1.070600e-07
C43913	-5.5678084e-11	1.082015e-07
S43913	-3.1568356e-08	1.064067e-07
C43914	-3.3683381e-08	1.062013e-07
S43914	-8.7634049e-09	1.074801e-07
C43915	-6.6782773e-08	1.053368e-07
S43915	-5.2749443e-10	1.069531e-07
C43916	5.4726544e-08	1.060869e-07
S43916	4.3536061e-08	1.051867e-07
C43917	-9.2081020e-09	1.065025e-07
S43917	9.0590265e-09	1.044871e-07
C43918	4.3263178e-08	1.045890e-07
S43918	-3.3680461e-08	1.049568e-07
C43919	-6.3694149e-08	1.030455e-07
S43919	-1.4220486e-08	1.060661e-07
C43920	1.8808566e-09	1.041695e-07
S43920	-7.4606297e-08	1.037046e-07
C43921	-5.8731178e-09	1.028426e-07
S43921	2.9845137e-08	1.042390e-07
C43922	-8.3149970e-08	1.026107e-07
S43922	-7.0667629e-08	1.023186e-07
C43923	-1.2112098e-08	1.036011e-07
S43923	5.5227357e-08	1.013520e-07
C43924	-8.1973924e-09	9.949913e-08
S43924	3.7306118e-08	1.017249e-07
C43925	3.9719568e-08	1.000996e-07
S43925	8.9697437e-09	1.013203e-07
C43926	2.7291353e-08	1.010856e-07
S43926	7.6301999e-09	9.926410e-08
C43927	-4.1277581e-08	9.954311e-08
S43927	-3.0384008e-08	9.924393e-08
C43928	8.2008644e-08	1.003932e-07
S43928	-2.9445239e-08	1.003189e-07
C43929	-4.7082652e-08	1.003380e-07
S43929	7.1514759e-08	1.004073e-07
C43930	3.7379297e-08	1.017116e-07
S43930	-1.0981390e-07	1.017113e-07
C43931	2.2572283e-08	1.022300e-07
S43931	1.2074527e-07	1.002819e-07
C43932	-7.3095764e-08	1.014483e-07
S43932	-1.5467084e-07	1.037902e-07
C43933	1.2815266e-07	1.024938e-07
S43933	9.5249015e-08	1.020436e-07
C43934	-6.5445875e-08	1.021075e-07
S43934	-1.2653685e-07	1.009296e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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C43935	6.3624982e-09	9.991103e-08
S43935	5.2366885e-08	1.008272e-07
C43936	-3.4921076e-08	9.958142e-08
S43936	-9.7162389e-08	1.020731e-07
C43937	1.1462774e-08	1.013966e-07
S43937	2.0929856e-07	1.010417e-07
C43938	9.7209366e-08	9.959341e-08
S43938	-2.5147645e-07	9.832463e-08
C43939	-5.1441936e-09	9.341211e-08
S43939	-2.4097238e-07	9.374694e-08
J440	-8.3845277e-08	1.097178e-07
C44001	2.5027495e-08	1.058256e-07
S44001	3.7711494e-08	1.114726e-07
C44002	3.8699895e-08	1.053236e-07
S44002	-1.4054219e-07	1.123879e-07
C44003	6.9910924e-08	1.107134e-07
S44003	3.7875622e-08	1.059446e-07
C44004	-9.4571838e-08	1.081600e-07
S44004	-6.1984886e-08	1.090647e-07
C44005	7.6764780e-08	1.090005e-07
S44005	-6.9008361e-09	1.071335e-07
C44006	-6.6915344e-08	1.073533e-07
S44006	2.7641489e-08	1.085913e-07
C44007	2.1132408e-08	1.061415e-07
S44007	-6.1322404e-08	1.092651e-07
C44008	-1.0051462e-08	1.079147e-07
S44008	1.9429406e-08	1.067570e-07
C44009	-1.7875317e-08	1.083239e-07
S44009	-5.3916423e-08	1.061382e-07
C44010	-8.1252772e-09	1.059279e-07
S44010	1.3796296e-09	1.072621e-07
C44011	-3.4129445e-08	1.060581e-07
S44011	-2.7533001e-08	1.066815e-07
C44012	-1.2831174e-08	1.066469e-07
S44012	4.8460331e-09	1.047161e-07
C44013	-1.9744109e-08	1.055210e-07
S44013	-7.0519670e-09	1.047685e-07
C44014	2.6980879e-09	1.038781e-07
S44014	3.7408208e-09	1.054653e-07
C44015	-2.7858028e-08	1.036759e-07
S44015	-8.9977712e-09	1.044315e-07
C44016	2.5083129e-08	1.038146e-07
S44016	-1.7175046e-08	1.033796e-07
C44017	-1.9504194e-08	1.035194e-07
S44017	-9.3650857e-09	1.025670e-07
C44018	1.4623217e-08	1.032378e-07
S44018	-8.6968837e-09	1.030372e-07
C44019	-5.0946421e-08	1.012542e-07
S44019	2.9876430e-08	1.033193e-07
C44020	-2.6869366e-10	1.033095e-07
S44020	5.4736963e-09	1.015211e-07
C44021	-2.8021921e-08	1.019244e-07
S44021	2.7059526e-08	1.016864e-07
C44022	5.0135172e-10	1.010288e-07
S44022	2.7136089e-08	1.016421e-07
C44023	3.5108894e-08	1.013051e-07
S44023	4.3273833e-08	9.954694e-08
C44024	1.0029482e-08	1.003743e-07
S44024	-1.4596515e-08	1.000748e-07
C44025	6.2465991e-08	9.766985e-08
S44025	-8.6267238e-09	9.942269e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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C44026	2.2777519e-08	9.814891e-08
S44026	4.5113559e-08	9.931580e-08
C44027	-2.9447575e-09	9.873051e-08
S44027	-2.2333392e-08	9.754089e-08
C44028	2.9101406e-08	9.849928e-08
S44028	4.4247675e-08	9.662894e-08
C44029	-6.6117598e-08	9.700444e-08
S44029	-1.8507632e-08	1.005984e-07
C44030	9.6454498e-08	9.886701e-08
S44030	-2.1389388e-08	9.893882e-08
C44031	-9.6966430e-08	1.017651e-07
S44031	2.5534310e-09	9.865604e-08
C44032	7.5581660e-08	9.868452e-08
S44032	-9.4467830e-08	1.008455e-07
C44033	-6.4382915e-08	1.008313e-07
S44033	1.1709556e-07	1.013722e-07
C44034	6.0367192e-08	1.012132e-07
S44034	-1.2935956e-07	1.000183e-07
C44035	-3.6176390e-08	9.917822e-08
S44035	1.1702986e-07	1.009849e-07
C44036	2.4569826e-08	9.886832e-08
S44036	-6.8916459e-08	9.916114e-08
C44037	2.2288898e-08	1.000838e-07
S44037	1.4535936e-07	9.926400e-08
C44038	6.7677013e-08	1.017271e-07
S44038	-9.1961953e-08	9.899855e-08
C44039	-1.3595264e-07	9.735984e-08
S44039	2.1756558e-08	9.876193e-08
C44040	-2.1633204e-08	9.496447e-08
S44040	1.5993251e-08	9.179009e-08
J441	-3.3276024e-08	1.064664e-07
C44101	-6.3999739e-08	1.031114e-07
S44101	-8.5643687e-08	1.095920e-07
C44102	1.7640638e-08	1.021313e-07
S44102	-3.5754118e-08	1.093873e-07
C44103	-6.4288537e-08	1.086331e-07
S44103	2.8366975e-08	1.035999e-07
C44104	-5.0963711e-09	1.057923e-07
S44104	-5.8104509e-08	1.055942e-07
C44105	-1.9470899e-09	1.069324e-07
S44105	8.2836094e-08	1.046751e-07
C44106	-6.2618656e-08	1.044630e-07
S44106	-2.7474127e-08	1.062452e-07
C44107	4.2036497e-08	1.040602e-07
S44107	1.8128836e-08	1.063016e-07
C44108	-4.8755363e-08	1.062396e-07
S44108	8.2055617e-10	1.036338e-07
C44109	1.5419221e-08	1.053448e-07
S44109	-1.0693595e-08	1.037910e-07
C44110	-4.5372255e-09	1.031475e-07
S44110	-5.0675974e-09	1.055971e-07
C44111	-1.6609377e-08	1.033836e-07
S44111	5.1934859e-09	1.044490e-07
C44112	-1.4501355e-08	1.041374e-07
S44112	4.2718285e-09	1.028262e-07
C44113	2.7251091e-08	1.034022e-07
S44113	-1.7230504e-08	1.027673e-07
C44114	2.6508287e-10	1.020128e-07
S44114	3.6006919e-08	1.027814e-07
C44115	2.3080778e-08	1.017617e-07
S44115	-9.3575807e-09	1.026463e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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C44116	-2.2234203e-08	1.013710e-07
S44116	-1.8726900e-08	1.016150e-07
C44117	4.5778608e-09	1.017854e-07
S44117	-2.6724965e-08	1.005883e-07
C44118	-1.3582809e-08	1.009255e-07
S44118	3.5526496e-08	1.007123e-07
C44119	2.1414147e-08	1.000616e-07
S44119	3.9257693e-09	1.016093e-07
C44120	8.8862305e-09	1.012207e-07
S44120	3.7028410e-08	9.915686e-08
C44121	1.5427706e-08	9.954121e-08
S44121	2.7090918e-09	1.008850e-07
C44122	2.8265045e-08	9.920314e-08
S44122	8.5690422e-09	1.002044e-07
C44123	2.1230467e-08	1.005416e-07
S44123	-2.7496310e-08	9.756372e-08
C44124	1.7381203e-08	9.783862e-08
S44124	-3.8913045e-08	9.909609e-08
C44125	-6.6573380e-09	9.728907e-08
S44125	-3.4850176e-08	9.871378e-08
C44126	1.6581195e-08	9.729601e-08
S44126	-3.0040747e-08	9.573803e-08
C44127	3.1391055e-08	9.772782e-08
S44127	3.1037485e-08	9.595984e-08
C44128	-2.3536347e-08	9.586017e-08
S44128	4.1738948e-08	9.658810e-08
C44129	2.2538394e-08	9.603561e-08
S44129	-1.7797511e-08	9.574796e-08
C44130	2.0000788e-09	9.757060e-08
S44130	5.5739008e-08	9.731745e-08
C44131	-8.2656397e-08	9.779498e-08
S44131	-5.1714992e-08	9.682779e-08
C44132	7.5243141e-08	9.730982e-08
S44132	6.3406204e-08	1.000163e-07
C44133	-7.9147576e-08	9.769890e-08
S44133	-4.5085970e-09	9.855250e-08
C44134	1.5059841e-07	9.924567e-08
S44134	-1.3236201e-08	9.953203e-08
C44135	-9.0034864e-08	9.823857e-08
S44135	6.0278922e-08	9.948196e-08
C44136	1.1828657e-07	9.737790e-08
S44136	-6.1703659e-08	9.977229e-08
C44137	-3.6224723e-08	9.829465e-08
S44137	1.1498838e-07	9.653055e-08
C44138	5.2547297e-09	9.943695e-08
S44138	-6.9590824e-08	9.707199e-08
C44139	-7.8777635e-08	9.895440e-08
S44139	6.1525569e-08	9.910420e-08
C44140	1.2520785e-07	9.698366e-08
S44140	1.3014247e-07	9.692997e-08
C44141	1.6870257e-07	9.086690e-08
S44141	2.4731741e-08	9.515460e-08
J442	5.6432733e-08	1.044029e-07
C44201	-2.1222975e-08	1.003334e-07
S44201	-4.0782780e-08	1.056887e-07
C44202	-2.1293667e-08	1.003815e-07
S44202	7.4422497e-08	1.068933e-07
C44203	-5.8586715e-08	1.052566e-07
S44203	-1.6449179e-08	1.005653e-07
C44204	6.8957129e-08	1.031467e-07
S44204	3.3569892e-08	1.038722e-07

Gravity Coeff.	Coefficient Value	Coefficient Error
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C44205	-3.1141195e-08	1.035507e-07
S44205	1.2926000e-08	1.020507e-07
C44206	4.7903144e-08	1.025520e-07
S44206	-4.1556313e-08	1.036046e-07
C44207	-1.7135517e-08	1.013294e-07
S44207	2.0384932e-08	1.033881e-07
C44208	7.8923492e-09	1.029675e-07
S44208	-3.8811555e-08	1.024152e-07
C44209	-4.6008194e-09	1.024596e-07
S44209	2.8214068e-08	1.013413e-07
C44210	-2.0347683e-08	1.016597e-07
S44210	-3.3993317e-08	1.026673e-07
C44211	7.4828517e-09	1.012588e-07
S44211	4.6838686e-08	1.015579e-07
C44212	-1.6894313e-08	1.023151e-07
S44212	-1.9932166e-08	1.006527e-07
C44213	6.6018387e-09	1.009281e-07
S44213	2.0210902e-08	1.003449e-07
C44214	-4.1150619e-08	9.982244e-08
S44214	-7.9286225e-09	1.012225e-07
C44215	3.4433615e-08	9.968924e-08
S44215	4.2162156e-08	1.002005e-07
C44216	-7.3675419e-08	1.000440e-07
S44216	3.6583269e-09	9.923646e-08
C44217	1.4697853e-08	9.993004e-08
S44217	-4.9453762e-09	9.853643e-08
C44218	1.2455760e-08	9.907180e-08
S44218	3.3982984e-08	9.865741e-08
C44219	1.7382956e-08	9.744557e-08
S44219	-3.4934453e-08	1.000328e-07
C44220	4.0459526e-09	9.896898e-08
S44220	1.5912627e-10	9.820799e-08
C44221	3.1296807e-08	9.771896e-08
S44221	-2.7154148e-08	9.870139e-08
C44222	-3.0115033e-08	9.806709e-08
S44222	7.0891173e-09	9.817439e-08
C44223	2.1208960e-09	9.884562e-08
S44223	-4.8098379e-08	9.660144e-08
C44224	-2.6845937e-08	9.640891e-08
S44224	-1.2099738e-08	9.754552e-08
C44225	-3.8106611e-08	9.586910e-08
S44225	-2.6633684e-08	9.731192e-08
C44226	-2.9478158e-08	9.571866e-08
S44226	-4.3236346e-09	9.599801e-08
C44227	1.4497656e-08	9.460381e-08
S44227	9.7595409e-09	9.464970e-08
C44228	-5.0788833e-09	9.589427e-08
S44228	2.5197405e-08	9.436235e-08
C44229	3.7560011e-08	9.311310e-08
S44229	1.4857506e-08	9.567186e-08
C44230	-6.7843662e-08	9.369010e-08
S44230	2.0946195e-08	9.502899e-08
C44231	4.5205910e-08	9.799608e-08
S44231	8.1873343e-09	9.390679e-08
C44232	-2.9802039e-08	9.595410e-08
S44232	6.2035784e-08	9.544819e-08
C44233	5.1243328e-08	9.698766e-08
S44233	-9.0988753e-08	9.681997e-08
C44234	4.8894902e-08	9.684304e-08
S44234	4.6108306e-08	9.591341e-08
C44235	-5.7371412e-08	9.722684e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
S44235	-7.6599200e-08	9.784240e-08
C44236	8.7751178e-08	9.605019e-08
S44236	2.8765339e-08	9.793300e-08
C44237	-1.2250163e-07	9.805089e-08
S44237	2.8238339e-08	9.585255e-08
C44238	9.7029565e-09	9.628306e-08
S44238	-6.7464499e-08	9.513789e-08
C44239	-4.3525785e-08	9.614690e-08
S44239	8.8253129e-08	9.717792e-08
C44240	3.1340835e-08	9.677672e-08
S44240	5.0742692e-08	9.839931e-08
C44241	6.3063417e-08	9.534393e-08
S44241	-1.2177969e-07	9.626754e-08
C44242	5.1397228e-08	9.321464e-08
S44242	-1.1406228e-07	9.122893e-08
J443	3.8311089e-08	1.010229e-07
C44301	1.8138426e-08	9.817438e-08
S44301	6.1715480e-08	1.037063e-07
C44302	-2.1728248e-08	9.738029e-08
S44302	5.9799499e-08	1.032312e-07
C44303	4.2474821e-08	1.029634e-07
S44303	-2.5671033e-08	9.875075e-08
C44304	1.0903151e-08	9.996120e-08
S44304	1.8927946e-08	1.004071e-07
C44305	-1.8918717e-08	1.018646e-07
S44305	-5.1100741e-08	9.961348e-08
C44306	1.9568999e-08	9.926236e-08
S44306	5.8074252e-10	1.004066e-07
C44307	-2.6272190e-08	9.940133e-08
S44307	-1.0419361e-08	1.014428e-07
C44308	-1.9612520e-08	1.002218e-07
S44308	2.0990618e-08	9.864076e-08
C44309	-1.1752609e-08	1.010912e-07
S44309	5.3004252e-09	9.919098e-08
C44310	1.9879849e-08	9.827121e-08
S44310	2.9799687e-08	9.977465e-08
C44311	-3.7414707e-08	9.922538e-08
S44311	-7.6270462e-09	1.001036e-07
C44312	1.6976752e-08	9.924076e-08
S44312	1.6607016e-09	9.804748e-08
C44313	-3.9731815e-08	9.903970e-08
S44313	5.1160806e-08	9.877102e-08
C44314	1.6430014e-08	9.781848e-08
S44314	-1.9915745e-08	9.837068e-08
C44315	3.0807689e-08	9.769138e-08
S44315	3.9796367e-08	9.831163e-08
C44316	-3.4640630e-08	9.736947e-08
S44316	-2.2513068e-08	9.787257e-08
C44317	1.6518539e-08	9.747214e-08
S44317	1.3910029e-08	9.697518e-08
C44318	-1.3082532e-08	9.741835e-08
S44318	-2.8976412e-08	9.678827e-08
C44319	3.3474442e-08	9.589060e-08
S44319	-1.6473729e-09	9.752758e-08
C44320	-2.2303361e-08	9.799015e-08
S44320	2.2830295e-09	9.569699e-08
C44321	-5.7184967e-09	9.634708e-08
S44321	-2.2363731e-08	9.651588e-08
C44322	-1.4152816e-09	9.567511e-08
S44322	3.7996428e-08	9.705275e-08
C44323	-6.1071074e-09	9.708333e-08
S44323	-9.6594886e-09	9.497407e-08
C44324	-3.2558103e-08	9.538917e-08
S44324	2.9523259e-08	9.624638e-08
C44325	-2.0963104e-08	9.412494e-08
S44325	2.2746732e-08	9.573444e-08
C44326	-5.1693051e-09	9.530690e-08
S44326	3.8497649e-08	9.414516e-08
C44327	-8.4957425e-09	9.487479e-08
S44327	1.5079892e-08	9.279388e-08
C44328	2.8245702e-08	9.288469e-08
S44328	-2.8243954e-08	9.295393e-08
C44329	-4.2122423e-09	9.282527e-08
S44329	2.7375312e-08	9.413189e-08
C44330	-4.3877660e-08	9.302646e-08
S44330	-1.7898704e-08	9.256166e-08
C44331	6.0099065e-08	9.321257e-08
S44331	3.6513357e-08	9.265602e-08
C44332	-3.9792488e-08	9.270314e-08
S44332	-2.6387651e-08	9.622261e-08
C44333	8.3226022e-08	9.355925e-08
S44333	-1.8498227e-08	9.441423e-08
C44334	-1.0157762e-07	9.580540e-08
S44334	-4.4406831e-09	9.438779e-08
C44335	2.6294601e-08	9.461362e-08
S44335	-5.5790658e-08	9.431919e-08
C44336	-3.5717416e-08	9.571366e-08
S44336	1.1109160e-07	9.548781e-08
C44337	-9.1847207e-08	9.577989e-08
S44337	-1.0472942e-08	9.437553e-08
C44338	4.9529124e-08	9.644528e-08
S44338	7.2467468e-08	9.402659e-08
C44339	-5.7880189e-08	9.280110e-08
S44339	6.7350569e-08	9.488290e-08
C44340	7.6991371e-08	9.492363e-08
S44340	2.0998540e-09	9.491281e-08
C44341	-2.3575375e-08	9.576308e-08
S44341	-2.7126871e-08	9.634880e-08
C44342	-4.2529075e-08	9.446950e-08
S44342	4.5042564e-08	9.441222e-08
C44343	-1.3434370e-07	9.185108e-08
S44343	3.8473353e-08	9.081397e-08
J444	-2.9743654e-08	9.885137e-08
C44401	2.9623966e-08	9.541658e-08
S44401	5.3043976e-08	1.005258e-07
C44402	1.7286038e-08	9.548567e-08
S44402	-1.4073100e-08	1.009067e-07
C44403	2.9081913e-08	9.992622e-08
S44403	-2.1747445e-08	9.577713e-08
C44404	-3.4583583e-08	9.793946e-08
S44404	-7.3100443e-09	9.839984e-08
C44405	-1.6292205e-08	9.839658e-08
S44405	-2.3588578e-08	9.705917e-08
C44406	-2.8836063e-08	9.741946e-08
S44406	1.0313940e-08	9.849402e-08
C44407	-5.4810579e-10	9.664716e-08
S44407	2.6162787e-09	9.799745e-08
C44408	-1.7640779e-08	9.799541e-08
S44408	4.0163171e-08	9.732996e-08
C44409	1.9477105e-08	9.727337e-08
S44409	-1.3174402e-08	9.666727e-08
C44410	6.3433390e-09	9.685629e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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S44410	5.1459949e-08	9.780602e-08
C44411	9.6231927e-09	9.648637e-08
S44411	-1.9393517e-08	9.666817e-08
C44412	1.8490167e-08	9.750065e-08
S44412	4.3843042e-08	9.629778e-08
C44413	-1.2996293e-08	9.626082e-08
S44413	-2.4309271e-08	9.604200e-08
C44414	6.4816045e-08	9.586049e-08
S44414	2.5137835e-08	9.678693e-08
C44415	-2.0060955e-08	9.519507e-08
S44415	-2.6447779e-08	9.607869e-08
C44416	4.6743174e-08	9.594886e-08
S44416	-9.5302173e-09	9.535155e-08
C44417	-2.4161158e-08	9.599269e-08
S44417	6.4431351e-09	9.453169e-08
C44418	-1.0410699e-08	9.483191e-08
S44418	-3.0667965e-08	9.499305e-08
C44419	3.2020383e-09	9.380441e-08
S44419	-1.4870457e-09	9.611622e-08
C44420	-9.4183866e-09	9.497010e-08
S44420	-8.4797264e-09	9.416565e-08
C44421	-1.6906235e-08	9.429711e-08
S44421	3.0754714e-08	9.529853e-08
C44422	3.4356048e-08	9.430711e-08
S44422	-2.8372158e-08	9.426274e-08
C44423	-1.9785670e-08	9.589907e-08
S44423	1.9474587e-08	9.292368e-08
C44424	5.2730012e-09	9.308777e-08
S44424	1.0322689e-08	9.473329e-08
C44425	2.1784367e-08	9.305591e-08
S44425	3.5190720e-08	9.457147e-08
C44426	3.0852679e-08	9.319469e-08
S44426	7.5296459e-09	9.249148e-08
C44427	1.1830510e-08	9.276141e-08
S44427	2.0748650e-08	9.274355e-08
C44428	1.1050935e-09	9.191930e-08
S44428	-2.1645332e-08	9.184946e-08
C44429	-2.9653143e-08	9.094771e-08
S44429	-2.6001333e-09	9.143340e-08
C44430	1.1936523e-08	9.152677e-08
S44430	-1.5426644e-08	9.212954e-08
C44431	-1.6816347e-08	9.235708e-08
S44431	1.0499541e-08	8.981637e-08
C44432	1.5501654e-08	9.189675e-08
S44432	-5.0887969e-08	9.104579e-08
C44433	6.2883733e-09	9.247360e-08
S44433	3.2028117e-08	9.308383e-08
C44434	-5.1770893e-08	9.205313e-08
S44434	-1.6114338e-08	9.250654e-08
C44435	3.2896111e-09	9.259765e-08
S44435	4.8339132e-08	9.364668e-08
C44436	-4.6817139e-08	9.212136e-08
S44436	5.6263374e-08	9.291905e-08
C44437	1.9740310e-08	9.373173e-08
S44437	2.1363464e-08	9.324817e-08
C44438	-4.4542965e-09	9.398684e-08
S44438	5.8644008e-08	9.210485e-08
C44439	1.0038068e-08	9.171992e-08
S44439	-3.2410972e-08	9.471629e-08
C44440	7.0754560e-08	9.198246e-08
S44440	3.1450106e-08	9.151125e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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C44441	-6.4624907e-08	9.263621e-08
S44441	-6.9461880e-08	9.336322e-08
C44442	4.7319447e-08	9.501355e-08
S44442	7.3875115e-08	9.308714e-08
C44443	1.3802338e-08	9.296676e-08
S44443	2.8233749e-08	9.280532e-08
C44444	5.0317667e-08	8.880631e-08
S44444	1.5393828e-07	9.143776e-08
J445	-3.5321302e-08	9.643913e-08
C44501	-2.5585873e-08	9.298831e-08
S44501	-3.2306207e-08	9.752477e-08
C44502	5.9713162e-09	9.319303e-08
S44502	-3.9022105e-08	9.822240e-08
C44503	-2.9153053e-08	9.695908e-08
S44503	1.6026519e-08	9.342070e-08
C44504	-8.2645637e-09	9.530240e-08
S44504	4.6055891e-09	9.577415e-08
C44505	2.2461230e-09	9.578675e-08
S44505	1.7742498e-08	9.455064e-08
C44506	1.9123978e-08	9.489622e-08
S44506	2.3700523e-08	9.566145e-08
C44507	1.5562155e-08	9.424411e-08
S44507	2.8430860e-08	9.548769e-08
C44508	2.4274731e-08	9.512816e-08
S44508	-2.6109950e-08	9.478649e-08
C44509	2.0124776e-08	9.527265e-08
S44509	1.1935502e-08	9.397586e-08
C44510	-3.5366294e-08	9.434576e-08
S44510	-2.3330635e-08	9.473381e-08
C44511	6.4200671e-08	9.401850e-08
S44511	-1.9040137e-08	9.476258e-08
C44512	-2.0968232e-08	9.429568e-08
S44512	2.5050328e-08	9.374039e-08
C44513	2.8028312e-08	9.426851e-08
S44513	-5.3808656e-08	9.403827e-08
C44514	-1.9925658e-09	9.331335e-08
S44514	1.5809287e-08	9.361363e-08
C44515	-3.0557592e-08	9.363688e-08
S44515	-6.6089061e-08	9.390268e-08
C44516	4.6261984e-08	9.286547e-08
S44516	3.1334612e-08	9.304299e-08
C44517	-4.9050426e-08	9.356318e-08
S44517	-6.3866974e-09	9.287855e-08
C44518	2.9973415e-08	9.309883e-08
S44518	1.3352164e-08	9.236477e-08
C44519	-6.7651397e-08	9.205843e-08
S44519	7.4466286e-09	9.316987e-08
C44520	1.9832702e-08	9.343204e-08
S44520	-8.4635638e-09	9.195787e-08
C44521	6.1297041e-09	9.205518e-08
S44521	2.9266266e-08	9.255225e-08
C44522	3.2020748e-09	9.210767e-08
S44522	-3.5903986e-08	9.298760e-08
C44523	-3.4675435e-09	9.266464e-08
S44523	2.7704831e-08	9.139111e-08
C44524	2.5484823e-08	9.181124e-08
S44524	-1.3173141e-08	9.285750e-08
C44525	3.0293736e-08	9.135844e-08
S44525	-8.1314096e-09	9.209763e-08
C44526	4.9219829e-09	9.231712e-08
S44526	-2.1870760e-08	9.117231e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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C44527	1.0703009e-08	9.125410e-08
S44527	-2.5829390e-08	9.020504e-08
C44528	-1.4896676e-08	9.057623e-08
S44528	1.5484515e-08	9.078558e-08
C44529	-2.6573107e-08	8.909120e-08
S44529	2.7605049e-09	9.062650e-08
C44530	6.7206718e-09	8.943745e-08
S44530	3.5961364e-09	8.937692e-08
C44531	-3.4282497e-08	9.086133e-08
S44531	9.3378258e-09	8.930481e-08
C44532	2.1763804e-08	8.804284e-08
S44532	-2.9236976e-08	9.059554e-08
C44533	-2.7378589e-08	8.951145e-08
S44533	1.9514374e-08	9.022450e-08
C44534	3.3564955e-08	9.171855e-08
S44534	1.1654695e-08	8.999351e-08
C44535	-2.0302403e-08	9.075094e-08
S44535	3.5258816e-08	8.986257e-08
C44536	1.8717139e-08	9.083032e-08
S44536	1.9393566e-09	9.099789e-08
C44537	6.1782076e-09	9.034855e-08
S44537	2.5807982e-08	9.042681e-08
C44538	-1.8426721e-08	9.124236e-08
S44538	-2.0313248e-08	9.133500e-08
C44539	3.6379643e-09	8.970096e-08
S44539	-3.1311743e-08	9.215618e-08
C44540	-4.9307271e-08	9.105860e-08
S44540	4.6194757e-08	9.128044e-08
C44541	-2.1564306e-08	9.014713e-08
S44541	-8.4242165e-08	8.935388e-08
C44542	-6.9567089e-09	9.168327e-08
S44542	1.2773718e-07	9.018352e-08
C44543	-2.7573837e-08	9.166307e-08
S44543	-9.1980421e-08	9.229598e-08
C44544	-8.5142664e-09	9.137418e-08
S44544	2.7315975e-08	9.095475e-08
C44545	8.0732914e-08	8.986454e-08
S44545	-8.8783725e-08	8.740918e-08
J446	1.1949080e-08	9.336629e-08
C44601	-8.4070516e-09	9.107924e-08
S44601	-3.9058454e-08	9.535460e-08
C44602	8.3613022e-09	9.053165e-08
S44602	-3.3713982e-09	9.465989e-08
C44603	-7.2684422e-09	9.489728e-08
S44603	4.5627559e-09	9.147610e-08
C44604	-1.5993848e-09	9.239926e-08
S44604	5.7314404e-09	9.256887e-08
C44605	1.5499789e-08	9.361804e-08
S44605	2.1205753e-08	9.252076e-08
C44606	7.3826203e-09	9.196643e-08
S44606	4.9477588e-09	9.274252e-08
C44607	1.1881474e-08	9.233850e-08
S44607	-9.6696118e-09	9.319072e-08
C44608	8.6729831e-09	9.229214e-08
S44608	-4.3679798e-09	9.203601e-08
C44609	-1.7241474e-08	9.282635e-08
S44609	-5.8820425e-09	9.205401e-08
C44610	1.3905620e-08	9.169429e-08
S44610	-2.8358346e-08	9.224438e-08
C44611	2.4524102e-09	9.188269e-08
S44611	1.1307464e-08	9.211549e-08
C44612	-8.6297564e-09	9.217948e-08
S44612	-4.5120492e-08	9.133735e-08
C44613	2.6919979e-08	9.158194e-08
S44613	1.0170231e-08	9.141781e-08
C44614	-4.9512973e-08	9.137835e-08
S44614	-8.0850382e-09	9.178241e-08
C44615	1.2164141e-08	9.055006e-08
S44615	-1.3919551e-08	9.126451e-08
C44616	-7.2085720e-09	9.139684e-08
S44616	3.0387526e-08	9.105156e-08
C44617	1.6331116e-08	9.092888e-08
S44617	-8.7678495e-09	8.996043e-08
C44618	-2.1352505e-09	9.080095e-08
S44618	1.9557251e-08	9.092377e-08
C44619	-1.6031926e-09	8.925536e-08
S44619	1.7326146e-08	9.119565e-08
C44620	1.5252997e-08	9.099962e-08
S44620	1.6286974e-08	8.968560e-08
C44621	-6.9080204e-09	9.022635e-08
S44621	-1.9266339e-08	9.044307e-08
C44622	-4.9851015e-09	8.975959e-08
S44622	1.9874743e-09	9.020583e-08
C44623	1.5095958e-08	9.120173e-08
S44623	9.9214310e-09	8.913577e-08
C44624	7.6013064e-09	8.928042e-08
S44624	-1.0571970e-08	9.019222e-08
C44625	3.2155399e-09	8.925630e-08
S44625	-1.7299250e-08	9.069421e-08
C44626	-8.2313977e-09	8.980017e-08
S44626	-3.8472067e-09	8.894007e-08
C44627	-2.1660754e-08	8.958310e-08
S44627	-1.7639903e-08	8.908661e-08
C44628	-1.7219684e-08	8.819059e-08
S44628	8.8450419e-09	8.870144e-08
C44629	3.3833914e-09	8.851150e-08
S44629	7.5502086e-09	8.833918e-08
C44630	-4.7827958e-09	8.777446e-08
S44630	2.4160636e-09	8.767822e-08
C44631	-6.1058805e-09	8.768959e-08
S44631	1.2998447e-08	8.714326e-08
C44632	2.2663011e-10	8.794197e-08
S44632	-1.9692231e-09	8.813612e-08
C44633	1.3243141e-09	8.740269e-08
S44633	-1.4804219e-09	8.712135e-08
C44634	3.6448123e-08	8.797256e-08
S44634	9.7228990e-09	8.796937e-08
C44635	5.5377521e-09	8.837782e-08
S44635	-1.6053961e-08	8.876328e-08
C44636	7.0932760e-09	8.791604e-08
S44636	5.9252930e-09	8.812801e-08
C44637	-2.6962860e-08	8.859764e-08
S44637	-2.5152022e-08	8.842158e-08
C44638	-3.5828671e-08	8.819985e-08
S44638	-1.3641302e-08	8.794940e-08
C44639	-1.5904377e-08	8.815697e-08
S44639	6.5905471e-09	8.959583e-08
C44640	-7.1595908e-08	8.885965e-08
S44640	2.0630899e-08	8.852531e-08
C44641	1.3640341e-08	8.954790e-08
S44641	-6.0453727e-09	8.804217e-08
C44642	-9.4185136e-08	8.786297e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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S44642	7.4693617e-08	8.710492e-08
C44643	2.9037684e-08	8.883939e-08
S44643	-6.7078028e-08	8.853292e-08
C44644	-1.0074632e-07	8.963756e-08
S44644	7.5387936e-08	8.963099e-08
C44645	4.2592381e-09	8.891632e-08
S44645	6.8822918e-09	8.945574e-08
C44646	-1.1991894e-07	8.663286e-08
S44646	-1.3749726e-08	8.714409e-08
J447	1.6907183e-08	9.107808e-08
C44701	-1.7509310e-08	8.828434e-08
S44701	-5.7342918e-09	9.155971e-08
C44702	1.0145471e-10	8.853525e-08
S44702	3.2445833e-09	9.231078e-08
C44703	-6.2074149e-09	9.117266e-08
S44703	1.4386119e-08	8.855786e-08
C44704	2.4393760e-08	9.014407e-08
S44704	7.2365529e-09	9.045269e-08
C44705	2.7602647e-08	9.004473e-08
S44705	-8.8434602e-10	8.953141e-08
C44706	-1.0620000e-08	8.992444e-08
S44706	-1.0432437e-08	9.040636e-08
C44707	-6.8417420e-09	8.943649e-08
S44707	-3.4669395e-08	8.972032e-08
C44708	5.0278339e-09	8.978709e-08
S44708	7.7583166e-09	8.995428e-08
C44709	-3.5769515e-08	8.960826e-08
S44709	-2.8116117e-08	8.917479e-08
C44710	2.8274678e-08	8.955816e-08
S44710	1.0838722e-08	8.941384e-08
C44711	-4.6502374e-08	8.905091e-08
S44711	2.1987650e-08	8.927599e-08
C44712	1.9565628e-08	8.922345e-08
S44712	-3.3596808e-08	8.894441e-08
C44713	-1.9266129e-08	8.893648e-08
S44713	3.5633598e-08	8.882752e-08
C44714	-5.3968733e-09	8.856127e-08
S44714	-2.3064450e-08	8.881060e-08
C44715	3.0878537e-09	8.820558e-08
S44715	5.1494149e-08	8.894946e-08
C44716	-1.5996239e-08	8.822587e-08
S44716	-2.4787375e-08	8.800036e-08
C44717	4.7566537e-08	8.865491e-08
S44717	1.9772990e-09	8.795470e-08
C44718	-3.1493462e-08	8.774388e-08
S44718	7.4036221e-09	8.762660e-08
C44719	4.4394382e-08	8.757531e-08
S44719	-2.5151947e-08	8.867037e-08
C44720	-8.4141985e-09	8.775097e-08
S44720	2.5288097e-09	8.719920e-08
C44721	-5.1931860e-09	8.750443e-08
S44721	-1.6494717e-08	8.795057e-08
C44722	-1.6273166e-08	8.754253e-08
S44722	2.2528862e-09	8.768940e-08
C44723	1.1295140e-08	8.797427e-08
S44723	-2.9978642e-08	8.665536e-08
C44724	-1.0404524e-08	8.686759e-08
S44724	-3.1948873e-09	8.808303e-08
C44725	-9.7325613e-09	8.702041e-08
S44725	-1.5854134e-08	8.720879e-08
C44726	-1.2216450e-09	8.774589e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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S44726	4.9148627e-09	8.679925e-08
C44727	-5.4353515e-09	8.678045e-08
S44727	2.0279045e-08	8.658923e-08
C44728	-4.6343551e-09	8.648871e-08
S44728	1.4114514e-08	8.683664e-08
C44729	1.8402031e-08	8.567507e-08
S44729	-3.3292419e-09	8.616795e-08
C44730	1.2663605e-08	8.592259e-08
S44730	-5.4643677e-09	8.578613e-08
C44731	2.6747561e-08	8.582956e-08
S44731	-1.2484454e-08	8.480534e-08
C44732	-1.5173687e-08	8.457561e-08
S44732	8.7135356e-09	8.577892e-08
C44733	1.6093165e-08	8.523727e-08
S44733	8.5223337e-09	8.618564e-08
C44734	-7.3582516e-09	8.540820e-08
S44734	-1.3031347e-08	8.451425e-08
C44735	2.7609469e-08	8.606267e-08
S44735	-3.0095784e-08	8.529224e-08
C44736	-4.3295959e-08	8.610820e-08
S44736	1.5072379e-08	8.592450e-08
C44737	-1.4116463e-08	8.548490e-08
S44737	-2.2543982e-08	8.551773e-08
C44738	-2.1881173e-08	8.606157e-08
S44738	2.2164212e-08	8.574729e-08
C44739	-1.6389112e-08	8.512291e-08
S44739	6.2160556e-09	8.599735e-08
C44740	-2.3025958e-08	8.687447e-08
S44740	2.0751782e-08	8.576637e-08
C44741	2.1981721e-08	8.663242e-08
S44741	2.9223450e-08	8.592907e-08
C44742	-4.2144978e-08	8.668759e-08
S44742	-2.2156929e-08	8.593475e-08
C44743	6.8936802e-08	8.521372e-08
S44743	-7.7484024e-09	8.521054e-08
C44744	-8.2139621e-08	8.592321e-08
S44744	-1.3259853e-08	8.675845e-08
C44745	6.8196031e-08	8.705909e-08
S44745	1.0988503e-08	8.741763e-08
C44746	-4.5737865e-09	8.686534e-08
S44746	-2.8146324e-08	8.702612e-08
C44747	3.2148722e-08	8.460836e-08
S44747	9.2611326e-08	8.551371e-08
J448	1.4880977e-09	8.834743e-08
C44801	9.6287835e-09	8.624125e-08
S44801	-1.6113141e-08	8.938540e-08
C44802	4.2040432e-10	8.616076e-08
S44802	-2.7515548e-09	8.922147e-08
C44803	1.3996778e-08	8.900503e-08
S44803	-3.4831413e-09	8.656422e-08
C44804	8.4641570e-09	8.764174e-08
S44804	-1.5412268e-08	8.749991e-08
C44805	2.8011487e-10	8.797377e-08
S44805	4.1200775e-09	8.739961e-08
C44806	-1.5893814e-08	8.713174e-08
S44806	-1.3213984e-08	8.774173e-08
C44807	3.9296495e-09	8.723204e-08
S44807	2.1007441e-08	8.772057e-08
C44808	-2.6061406e-08	8.713429e-08
S44808	-6.6596018e-09	8.723530e-08
C44809	1.0804373e-08	8.759862e-08

Gravity Coeff.	Coefficient Value	Coefficient Error	Gravity Coeff.	Coefficient Value	Coefficient Error
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S44809	4.0882404e-11	8.692870e-08	C44840	-1.5809706e-08	8.329562e-08
C44810	-1.0841151e-08	8.688817e-08	S44840	-1.4410580e-08	8.247299e-08
S44810	2.0948481e-08	8.686168e-08	C44841	4.0714772e-09	8.384949e-08
C44811	-1.3264507e-08	8.666764e-08	S44841	1.2604527e-08	8.330166e-08
S44811	-2.6422748e-08	8.720525e-08	C44842	-1.3800252e-08	8.387503e-08
C44812	2.1749970e-08	8.665255e-08	S44842	-3.5182784e-08	8.353732e-08
S44812	2.5355606e-08	8.646354e-08	C44843	1.8524620e-09	8.343553e-08
C44813	-4.3381115e-08	8.667301e-08	S44843	1.1767424e-08	8.381659e-08
S44813	-3.2178408e-09	8.653223e-08	C44844	-3.0326778e-08	8.243256e-08
C44814	2.2286785e-08	8.619935e-08	S44844	-6.8425723e-08	8.314031e-08
S44814	-1.8745764e-08	8.626192e-08	C44845	1.9549841e-10	8.370703e-08
C44815	-1.8619818e-08	8.607082e-08	S44845	5.0913733e-08	8.395620e-08
S44815	3.9519971e-08	8.636038e-08	C44846	-3.4382593e-08	8.412618e-08
C44816	7.0026563e-09	8.596387e-08	S44846	-9.7805695e-08	8.511717e-08
S44816	-4.5388529e-08	8.581407e-08	C44847	-1.1459361e-08	8.448181e-08
C44817	1.6326195e-10	8.601075e-08	S44847	5.5872313e-08	8.445060e-08
S44817	1.0449135e-08	8.535502e-08	C44848	1.0523900e-07	8.368006e-08
C44818	5.1857949e-09	8.575959e-08	S44848	-5.1514798e-08	8.221505e-08
S44818	-1.4056234e-08	8.568796e-08	J449	6.5489584e-09	8.609112e-08
C44819	3.2181814e-09	8.486643e-08	C44901	8.9076707e-10	8.405830e-08
S44819	1.4954568e-09	8.564828e-08	S44901	7.8568898e-09	8.682893e-08
C44820	-2.5955619e-08	8.606634e-08	C44902	-9.2734735e-09	8.406464e-08
S44820	-1.1397374e-08	8.513927e-08	S44902	6.2426409e-09	8.687830e-08
C44821	2.0555153e-08	8.496307e-08	C44903	-6.0064278e-09	8.645959e-08
S44821	7.6160000e-09	8.499750e-08	S44903	-1.8792990e-08	8.444719e-08
C44822	-2.7547333e-08	8.501455e-08	C44904	-7.3303923e-09	8.517740e-08
S44822	2.2712190e-08	8.555443e-08	S44904	7.7010707e-09	8.551424e-08
C44823	7.4004911e-09	8.544083e-08	C44905	-2.4894176e-08	8.556783e-08
S44823	-1.4973663e-08	8.456142e-08	S44905	-1.8560282e-09	8.511014e-08
C44824	-1.7284037e-08	8.455666e-08	C44906	-1.8493944e-09	8.510361e-08
S44824	8.2200337e-09	8.504539e-08	S44906	-6.4463478e-09	8.539324e-08
C44825	-2.7226993e-09	8.460841e-08	C44907	-5.1232966e-09	8.508544e-08
S44825	-8.5985806e-09	8.516219e-08	S44907	2.3958341e-08	8.516674e-08
C44826	-2.0734906e-09	8.475729e-08	C44908	-1.5881304e-08	8.485239e-08
S44826	3.6331754e-09	8.443372e-08	S44908	-7.8398148e-09	8.532569e-08
C44827	7.6842845e-09	8.481760e-08	C44909	2.7700975e-08	8.489268e-08
S44827	7.1300253e-09	8.436195e-08	S44909	1.1436671e-08	8.474666e-08
C44828	1.6408897e-08	8.386742e-08	C44910	-1.5372158e-08	8.500824e-08
S44828	1.3811396e-08	8.424651e-08	S44910	4.4166545e-09	8.480145e-08
C44829	1.1422888e-09	8.393769e-08	C44911	1.1582548e-08	8.446446e-08
S44829	-4.9809448e-09	8.398270e-08	S44911	-6.4842058e-09	8.439357e-08
C44830	-2.5116256e-09	8.336543e-08	C44912	-9.2414089e-09	8.476036e-08
S44830	-1.7863835e-08	8.323014e-08	S44912	1.6450206e-08	8.438865e-08
C44831	9.1596577e-09	8.331976e-08	C44913	5.8809623e-09	8.411752e-08
S44831	-1.3775049e-08	8.322886e-08	S44913	-1.4671494e-08	8.408740e-08
C44832	-1.4415626e-08	8.257351e-08	C44914	2.7048278e-09	8.413055e-08
S44832	4.5487010e-09	8.308569e-08	S44914	2.2443093e-08	8.436617e-08
C44833	1.3310608e-08	8.307954e-08	C44915	-9.0914213e-11	8.352573e-08
S44833	1.0676628e-08	8.249467e-08	S44915	-1.0621618e-08	8.403922e-08
C44834	-2.4909663e-08	8.343426e-08	C44916	-8.9844911e-09	8.404389e-08
S44834	5.1202545e-09	8.284175e-08	S44916	6.9097936e-09	8.360668e-08
C44835	9.0302111e-10	8.211422e-08	C44917	-1.9918539e-08	8.373667e-08
S44835	-1.1854216e-08	8.280768e-08	S44917	2.2371947e-09	8.316316e-08
C44836	-3.9257197e-08	8.291572e-08	C44918	1.3898367e-08	8.344012e-08
S44836	4.8978898e-09	8.334385e-08	S44918	-1.2708943e-08	8.346606e-08
C44837	8.6826059e-09	8.307266e-08	C44919	-1.4946928e-09	8.277932e-08
S44837	1.9745163e-08	8.334150e-08	S44919	2.6155789e-08	8.382063e-08
C44838	-1.4660556e-08	8.282963e-08	C44920	-7.6137832e-10	8.329165e-08
S44838	7.2982370e-09	8.274768e-08	S44920	4.2781649e-09	8.278833e-08
C44839	2.4438337e-08	8.269854e-08	C44921	-4.7243797e-09	8.313412e-08
S44839	2.3039269e-08	8.353328e-08	S44921	8.2842470e-09	8.328310e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
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C44922	1.9928742e-08	8.260351e-08
S44922	1.2955183e-08	8.280617e-08
C44923	-4.8882423e-09	8.354725e-08
S44923	7.7716239e-09	8.247134e-08
C44924	8.4972897e-10	8.229214e-08
S44924	2.4604864e-09	8.286781e-08
C44925	-7.7870300e-09	8.226063e-08
S44925	1.2744926e-08	8.281068e-08
C44926	3.7273687e-09	8.282324e-08
S44926	-2.0418014e-09	8.216570e-08
C44927	-7.4437084e-09	8.230615e-08
S44927	8.7781950e-09	8.221130e-08
C44928	1.8215822e-08	8.192102e-08
S44928	-1.9898930e-08	8.234522e-08
C44929	-1.3636038e-08	8.170552e-08
S44929	-5.4252016e-09	8.160384e-08
C44930	-1.4165888e-08	8.162045e-08
S44930	-2.1214776e-08	8.141867e-08
C44931	-2.8746349e-08	8.100245e-08
S44931	1.2729440e-08	8.089896e-08
C44932	8.3704560e-09	8.069745e-08
S44932	6.2067412e-09	8.115975e-08
C44933	9.9805197e-09	8.041973e-08
S44933	3.5799232e-09	8.065629e-08
C44934	1.0702592e-08	8.064035e-08
S44934	5.5031962e-09	8.048210e-08
C44935	-1.8624471e-08	8.090252e-08
S44935	1.5727839e-08	8.051063e-08
C44936	-5.8907610e-09	8.024600e-08
S44936	8.0526982e-09	7.996491e-08
C44937	1.2335807e-08	8.047854e-08
S44937	2.3810648e-08	8.079377e-08
C44938	8.4382465e-09	8.045650e-08
S44938	-2.0399502e-08	8.053020e-08
C44939	-8.4554794e-09	7.985617e-08
S44939	1.6213589e-08	8.047886e-08
C44940	-1.4995707e-08	8.066494e-08
S44940	-2.6609336e-08	8.018752e-08
C44941	-1.4699992e-08	8.019260e-08
S44941	9.8634454e-09	8.024486e-08
C44942	-3.8481360e-09	8.064661e-08
S44942	-1.7196259e-08	8.108553e-08
C44943	-2.3254080e-08	8.114144e-08
S44943	7.1096178e-09	8.097077e-08
C44944	1.7449235e-08	8.069506e-08
S44944	-3.5851499e-08	8.118852e-08
C44945	-3.9064986e-08	8.024579e-08
S44945	2.4718079e-08	8.049121e-08
C44946	3.0135902e-08	8.106823e-08
S44946	-5.5080727e-08	8.151782e-08
C44947	-4.1867781e-08	8.215107e-08
S44947	6.4084148e-08	8.190159e-08
C44948	2.3666029e-08	8.207181e-08
S44948	4.6738435e-08	8.200513e-08
C44949	-3.7877776e-08	8.086008e-08
S44949	-3.4548306e-08	8.099322e-08
J450	-1.4466446e-08	8.346093e-08
C45001	-7.8728533e-09	8.145680e-08
S45001	9.8914029e-09	8.383020e-08
C45002	-1.3589958e-09	8.157283e-08
S45002	-5.9406075e-09	8.410463e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
~~	~~~~~~~~~~~~~~	~~~~~~~~~~~
C45003	1.2041555e-08	8.350213e-08
S45003	5.8534442e-10	8.182209e-08
C45004	-4.8972826e-09	8.285089e-08
S45004	1.0467839e-08	8.255304e-08
C45005	1.7790673e-10	8.279106e-08
S45005	-8.2429851e-09	8.235544e-08
C45006	2.5899397e-08	8.228819e-08
S45006	2.3703964e-08	8.289651e-08
C45007	-2.0330180e-08	8.239014e-08
S45007	-4.0470537e-09	8.246912e-08
C45008	4.3440105e-08	8.227139e-08
S45008	-7.6612633e-09	8.246095e-08
C45009	-9.2418264e-09	8.245914e-08
S45009	1.9534588e-08	8.208032e-08
C45010	3.0316086e-09	8.223716e-08
S45010	-2.9564223e-08	8.194389e-08
C45011	1.3405510e-08	8.193855e-08
S45011	2.3894304e-08	8.214180e-08
C45012	-3.1133612e-08	8.170512e-08
S45012	-7.4117253e-09	8.170566e-08
C45013	3.1105554e-08	8.171495e-08
S45013	-1.5643002e-09	8.170964e-08
C45014	-1.2531612e-08	8.137612e-08
S45014	1.7665513e-08	8.140984e-08
C45015	2.2386464e-08	8.118715e-08
S45015	-2.3726013e-08	8.159534e-08
C45016	-1.6714992e-08	8.122083e-08
S45016	3.1276003e-08	8.090915e-08
C45017	-5.2249167e-09	8.115112e-08
S45017	-2.0244554e-08	8.088407e-08
C45018	4.6828882e-10	8.073259e-08
S45018	2.4551319e-08	8.074691e-08
C45019	-8.6036998e-09	8.037841e-08
S45019	-1.9435739e-08	8.114660e-08
C45020	2.4503548e-08	8.065073e-08
S45020	-9.6370923e-11	8.046449e-08
C45021	-2.2454655e-08	8.044974e-08
S45021	7.5105929e-09	8.037825e-08
C45022	3.3223197e-08	8.035508e-08
S45022	-2.3802322e-08	8.048355e-08
C45023	-2.4962748e-08	8.024972e-08
S45023	4.0756754e-09	7.987598e-08
C45024	1.0177949e-08	7.998444e-08
S45024	-8.9989129e-09	8.051533e-08
C45025	-3.9844990e-10	7.981147e-08
S45025	1.0569643e-08	7.982244e-08
C45026	7.8319309e-09	7.992259e-08
S45026	-9.2597496e-09	7.977333e-08
C45027	8.4784187e-09	7.979721e-08
S45027	-7.1714497e-09	7.960396e-08
C45028	-1.7152000e-08	7.949010e-08
S45028	-1.4668697e-08	7.953103e-08
C45029	-1.2443591e-08	7.926114e-08
S45029	5.1205222e-09	7.927769e-08
C45030	-9.6123147e-11	7.892056e-08
S45030	3.5222853e-09	7.897892e-08
C45031	-1.7102642e-08	7.867166e-08
S45031	1.8584219e-08	7.873262e-08
C45032	2.0529187e-08	7.812387e-08
S45032	-8.0317573e-09	7.847970e-08
C45033	-7.8426179e-10	7.840854e-08

Gravity Coeff.	Coefficient Value	Coefficient Error
~~	~~~~~~~~~~~~~~	~~~~~~~~~~~~
S45033	1.9241129e-09	7.812105e-08
C45034	1.4391609e-08	7.828821e-08
S45034	-1.4395123e-08	7.767009e-08
C45035	5.1405103e-09	7.787644e-08
S45035	6.7350539e-09	7.816649e-08
C45036	-6.6126199e-09	7.785004e-08
S45036	-4.1342710e-09	7.818534e-08
C45037	2.6995016e-09	7.755263e-08
S45037	-1.0237175e-09	7.756956e-08
C45038	1.1463750e-08	7.806088e-08
S45038	-1.7704561e-08	7.785023e-08
C45039	-2.2724032e-08	7.760806e-08
S45039	-2.7610438e-09	7.781637e-08
C45040	-4.8725096e-09	7.775397e-08
S45040	-1.1173770e-08	7.732504e-08
C45041	-2.1226486e-08	7.774923e-08
S45041	7.9442070e-09	7.770850e-08
C45042	1.8588205e-08	7.746051e-08
S45042	-5.4384927e-09	7.785456e-08
C45043	-2.4106433e-08	7.825721e-08
S45043	-5.9899267e-09	7.826471e-08
C45044	2.5298850e-08	7.827896e-08
S45044	-3.6412589e-09	7.874797e-08
C45045	-3.6432343e-08	7.842981e-08
S45045	-1.5339193e-08	7.835732e-08
C45046	4.3804064e-08	7.803975e-08
S45046	9.8064541e-09	7.795706e-08
C45047	-4.7896151e-08	7.887331e-08
S45047	2.5631233e-08	7.864225e-08
C45048	2.3557483e-08	7.954750e-08
S45048	2.7576675e-08	7.910605e-08
C45049	-1.0719030e-08	7.920531e-08
S45049	-1.4532804e-08	7.954210e-08
C45050	-4.4952447e-08	7.869381e-08
S45050	8.8953368e-08	7.866008e-08

APPENDIX 9.6 DSN TRACKING STATION COORDINATES

A tracking station location is specified in cylindrical coordinates and referenced to the earth's mean pole, equator and prime meridian of 1903.0.

TABLE 9.6-1 DSN STATION COORDINATES

DSN Station	Spin Radius U (km)	Z Height V (km)	East Longitude λ (deg)
15	5204.234 3194	3676.670 034	243.112 806 935
45	5205.494 6968	-3674.381 393	148.977 683 311
65	4862.717 2271	4114.748 765	355.748 579 509

These tracking stations are also referred to as the high efficiency stations (HEF).

25	5209.635 9783	3669.040 895	243.124 638 433
34	5205.482 0033	-3674.375 098	148.981 962 157
54	4862.911 3109	4114.504 583	355.746 944 293

These tracking stations are also referred to as the beam waveguide stations (BWG).

APPENDIX 9.7 SOLAR RADIATION PRESSURE MODEL

Simplified models used during planning to account for solar radiation pressure (SRP) and constant non-gravitational (NG) accelerations are:

$$\ddot{r} = \frac{k}{r^2}\left[\sum_{1}^{3}(G(i) * U(i))\right] + \sum_{1}^{3}(a(i) * U(i))$$

where

A = area = 12.0 m^2
m = mass = 1060. kg (injected mass)
C = $1.01 \times 10^8 \ \frac{km^3\ kg}{s^2\ m^2}$

P = shadow factor

k = ACP/m = $1.19 \times 10^6 \ km^3/s^2$.

G(i) (i.e. Gr, Gx, Gy) are non-dimensional coefficients whose values are able to be estimated from analysis of the tracking data. In addition, the constant acceleration model (a[i]) is being used to provide an assessment of error due to spacecraft self-induced accelerations namely angular momentum desaturations (AMD).

For planning, uncertainties associated with this model are as follows:

Model Parameter		Uncertainty (1 σ)
SRP:	Gr	0.13 (or 10%)
	Gx, Gy	0.01
NG:	Acceleration (km/s^2)	1.5×10^{-12}

During flight operations, the SRP model shall be significantly more complex than given above.

APPENDIX 9.8 MARS ATMOSPHERIC DENSITY MODEL (AEROBRAKING)

The atmospheric density estimates used during planning for the aerobraking (AB) phase are taken from the MARS GRAM software obtained from Marshall Space Flight Center (Ref. 9.8-1). A summary of nominal densities as a function of altitude (110 km) and longitude and latitude are shown in the following two figures.

For these results, the epoch was 10/1/97 with the spacecraft's longitude and latitude being 212.4 deg and 33.7 deg respectively. At this time, the sub-solar point was 124 .6 deg, -4.3 deg; thus the sun-Mars-spacecraft angle was close to 90 deg.

Fig. 9.8-1 Latitude and Longitude Variation of the Mars Atmospheric Density at 110 km Altitude on 10/01/97.
Fig. 9.8-2 Mars Atmospheric Density at 110 km Altitude Over the Aerobraking Time Period.

The atmospheric densities used for the six AB simulations in Section 5 are given in Tables 5.5 and 5.6. In addition, the density variation throughout AB is given in Fig. 3.6.

Note that on 8/1/96, an updated version of the Mars-GRAM software (version 3.5) was delivered to the MGS Navigation Team by J. Justus. This updated software should be used for the aerobraking operations. (Reference: Mars Atmospheric Density Working Group Meeting at JPL on June 18, 1996.)

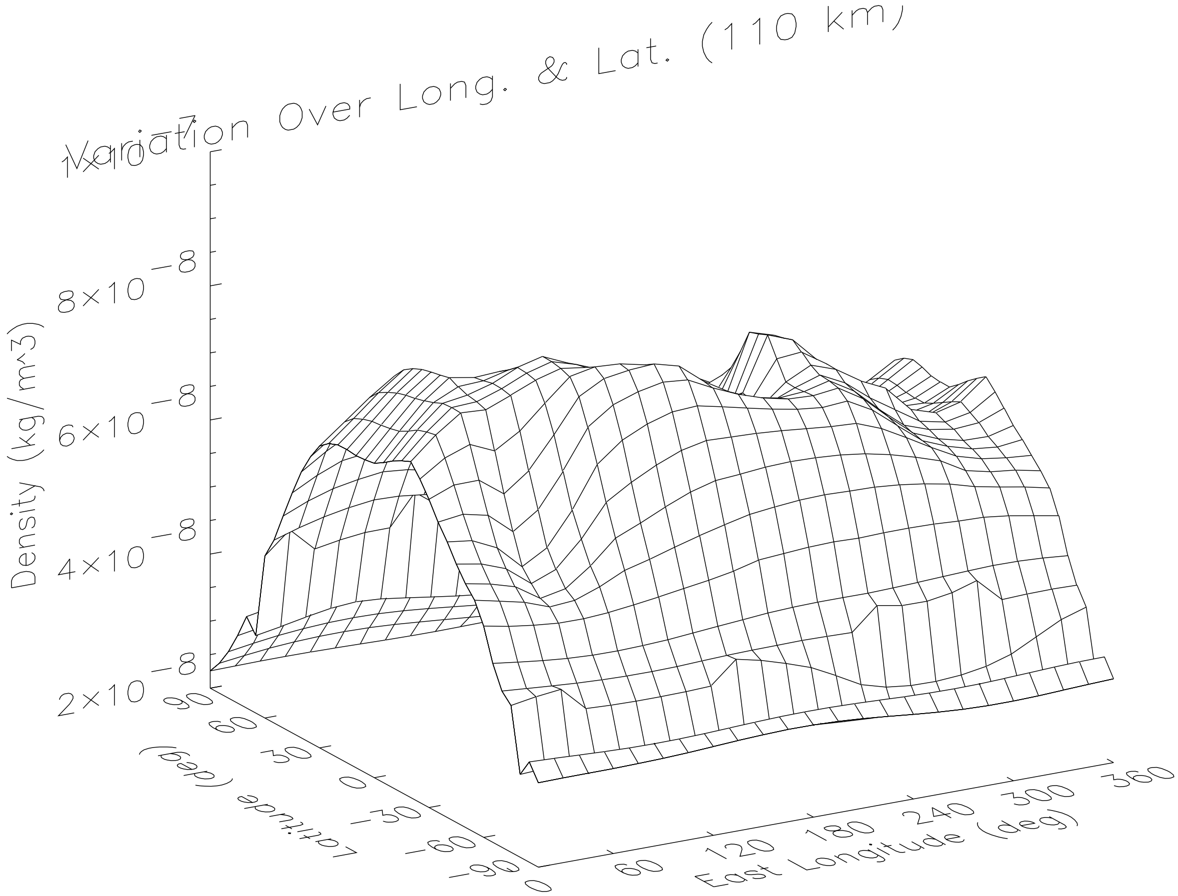

Figure 9.8-1 Latitude and Longitude Variation of the Mars Atmospheric Density at 110 km Altitude on 10/01/97

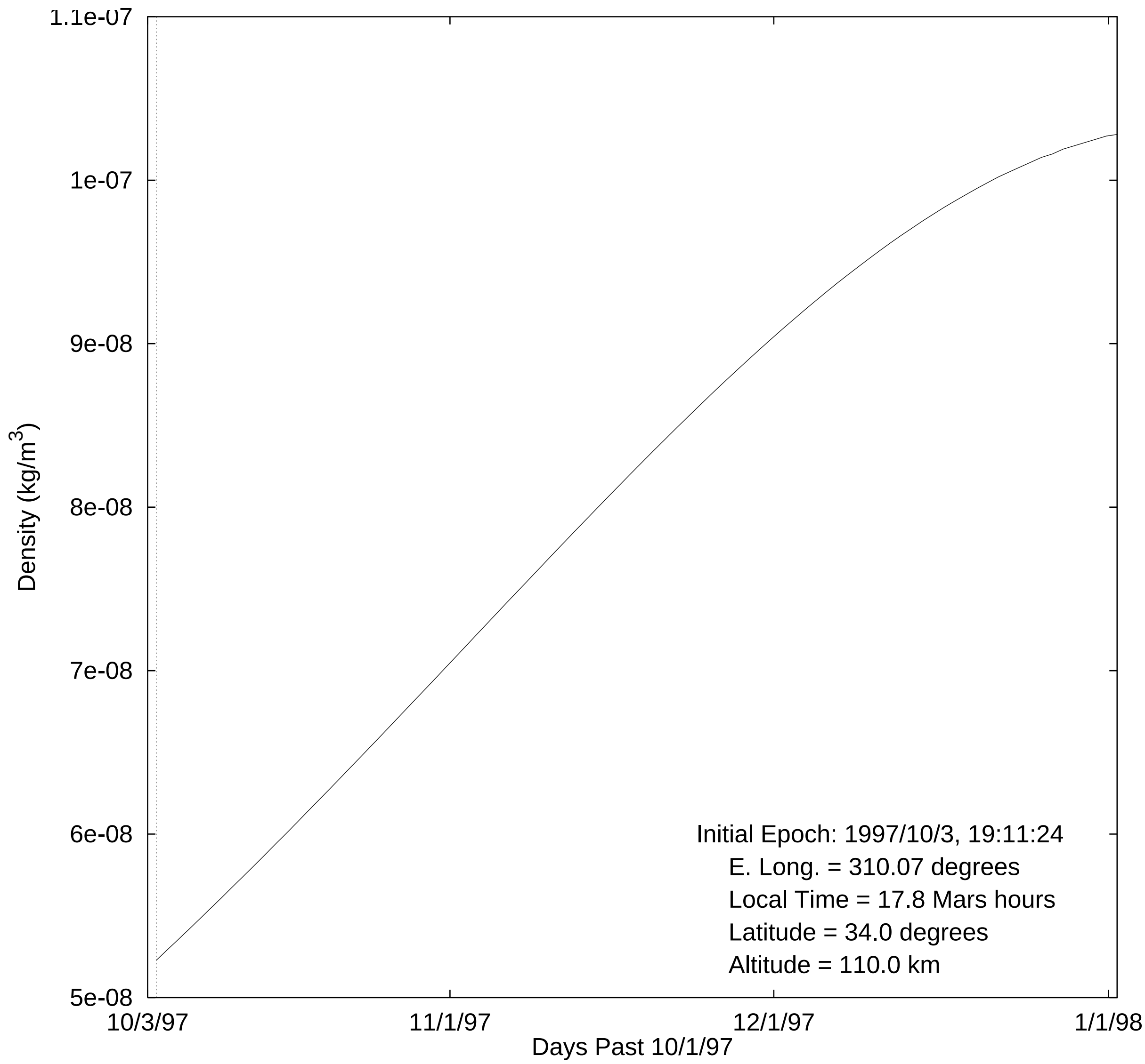

Figure 9.8-2 Mars Atmospheric Density at 110 km Altitude Over the Aerobraking Time Period

APPENDIX 9.9 MARS ATMOSPHERIC DENSITY MODEL (MAPPING ORBIT)

The current a priori Mars atmospheric density model at the MGS mapping orbit (378.1 km index altitude) is summarized in the following two figures. It is given a) for a 5 year interval, b) for 2 orbital eccentricities and c) at several confidence values (i.e. 50%, 90%, 95%, 99.0% and 99.9%).

Long-term average densities (1/1/98 to 1/1/00) are summarized as follows (e = 0.007) .

TABLE 9.9-1 LONG-TERM AVERAGE DENSITIES DURING MAPPING

Density (x 10^{-14} kg/m^3)	Confidence (%)
1.26	50.
5.18	90.
7.77	95.
16.7	99.
35.4	99.9

Fig. 9.9-1 Orbit averaged atmospheric density during mapping (e = 0.007).

Fig. 9.9-2 Orbit averaged atmospheric density during mapping (e = 0.014).

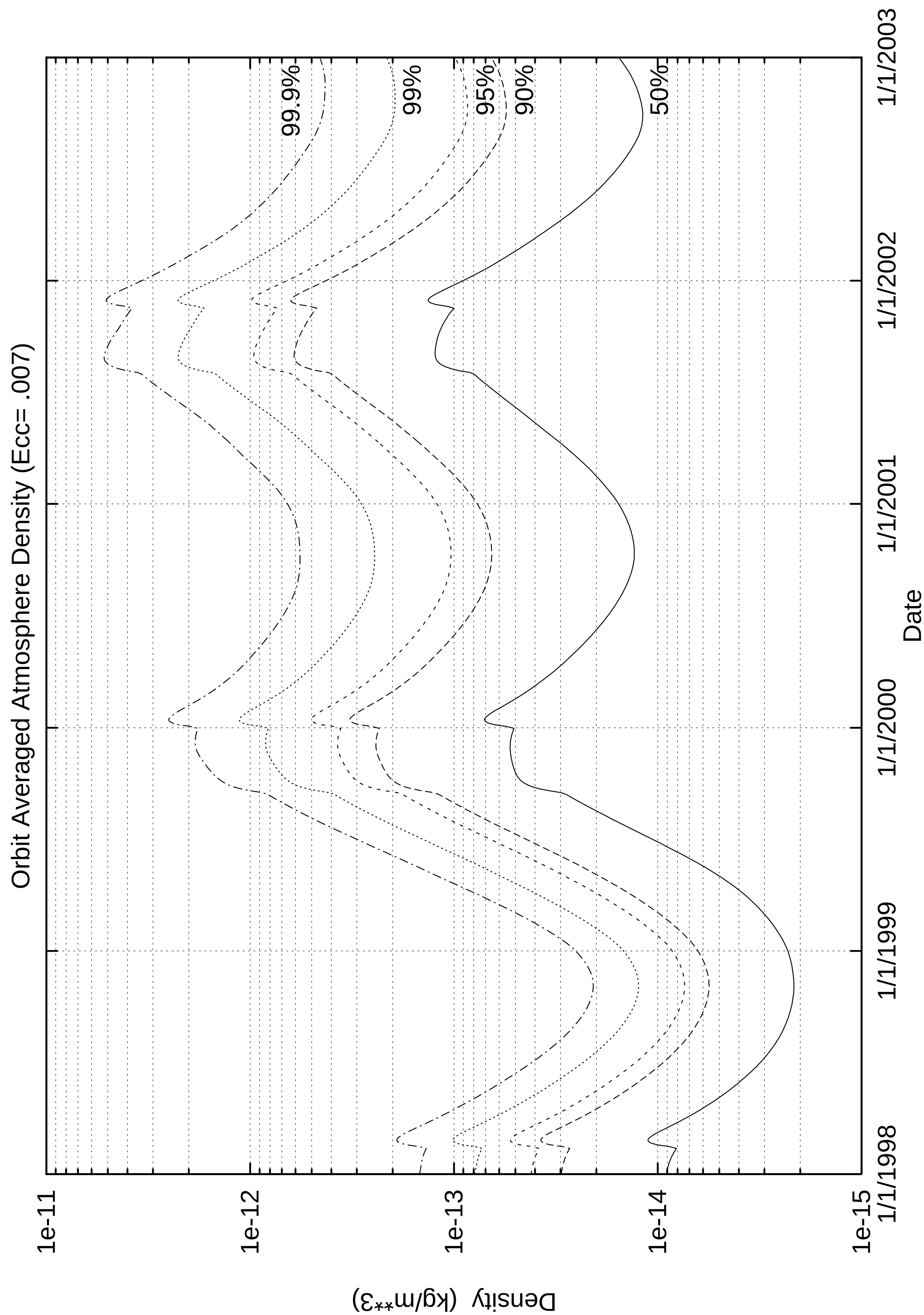

Figure 9.9-1 Orbit Averaged Atmospheric Density for Mapping (e = 0.007)

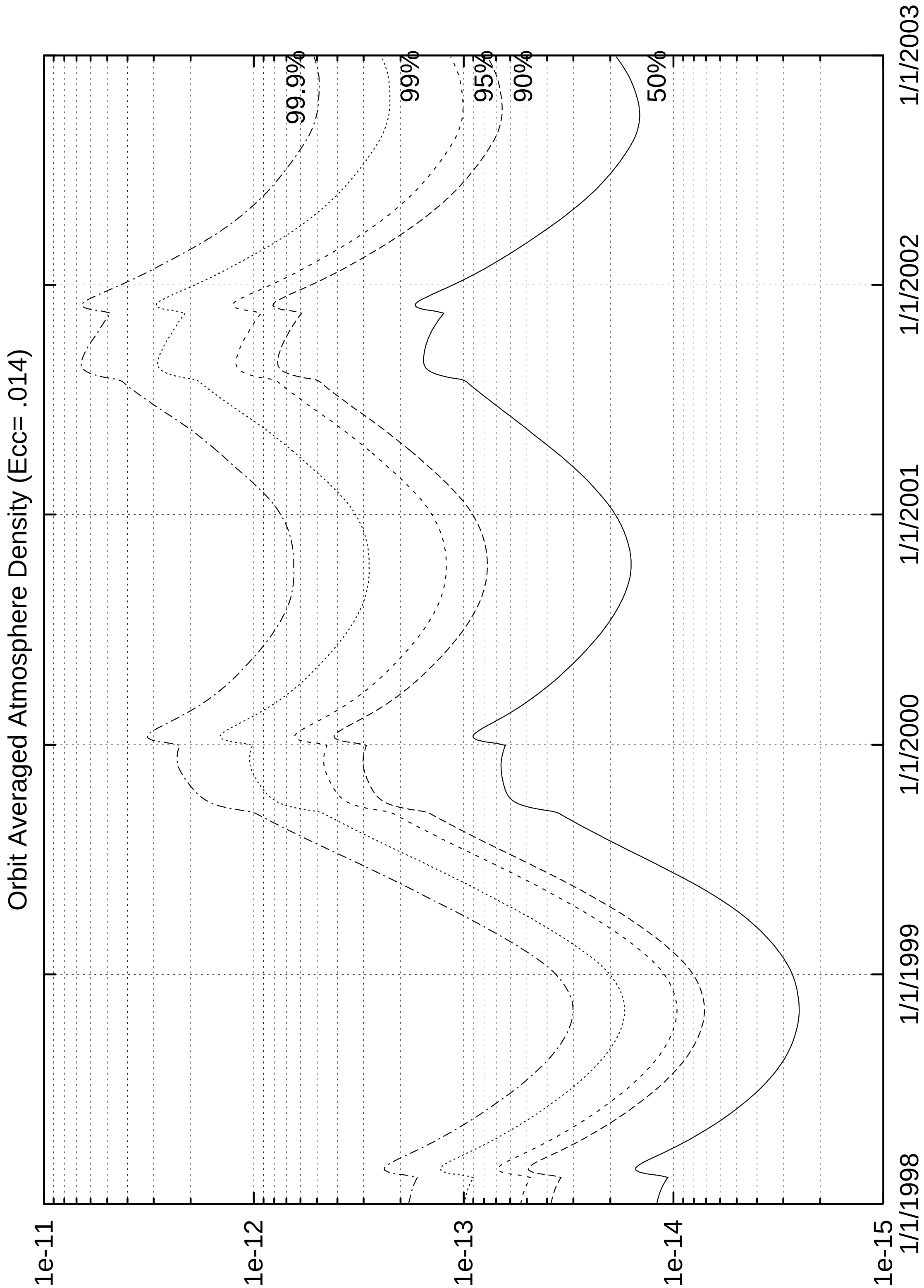

Figure 9.9-2 Orbit Averaged Atmospheric Density for Mapping (e = 0.014)

APPENDIX 9.10 INITIAL CONDITIONS FOR COVARIANCE ANALYSIS

- PHASE/PURPOSE
  Injection / OD after Injection

EPOCH (ET)
11/05/96, 18:26:17

	TRACKING DATA			ESTIMATION (1,1A)	
	Doppler (mm/s)	Range (m)	Dif-D (mm/s)	Estimate	Consider
N :	120	27	--	State	Pl Eph, Stats
σ :	0.2	5	--		SRP, GM3, NG

Data arc : 2 hours

- PHASE/PURPOSE
  Interplanetary / OD for MOI

EPOCH (ET)
02/27/97, 00:00:00

	TRACKING DATA			ESTIMATION (2B)	
	Doppler (mm/s)	Range (m)	Dif-D (mm/s)	Estimate	Consider
N :	2170	518	--	State	Pl Eph, Stats
σ :	0.2	5	--	SRP, AC	AMDs, GM4

Data arc : 185 days

- PHASE/PURPOSE
  Orbit Insertion / OD for AB-1

EPOCH (ET)
09/10/97, 02:29:49
(For 11/3/96 L)

	TRACKING DATA			ESTIMATION (2B)	
	Doppler (mm/s)	Range (m)	Dif-D (mm/s)	Estimate	Consider
N :	581	--	--	State, AC,	Grav (25x25),
σ :	0.2	--	--	Grav (4x4)	Density(ρ, H), GM4, Stats, Pl Eph

Data arc : 48 hours (1 orbit)

APPENDIX 9.10 INITIAL CONDITIONS FOR COVARIANCE ANALYSIS

- PHASE/PURPOSE: Walkin; P= 48.0 hrs /Density determ
  EPOCH (ET): 9/20/97, 02:07:00

	TRACKING DATA			ESTIMATION (10B)	
	Doppler (mm/s)	Range (m)	Dif-D (mm/s)	Estimate	Consider
N :	294; 404*	--	--	State, TH(P1),	Grav (25x25),
σ :	1.0; 1.0*	--	--	ρ_o (P1),	NG Accel,
	(varied data weights)			Grav (4x4)	GM4, ρ_o (P2...),

Data arc : 52 hours (i.e. 4.5 hrs past P1) (Also solutions 1E , 5A, 9)
* 72 hours (i. e. up to A2)

- PHASE/PURPOSE: Walkin; P= 48.0 hrs /Density determ
  EPOCH (ET): 9/20/97, 02:07:00

	TRACKING DATA			ESTIMATION (1B)	
	Doppler (mm/s)	Range (m)	Dif-D (mm/s)	Estimate *	Consider
N :	294	--	--	State,	Grav (25x25)
σ :	0.2	--	--	ρ_o (P1)	

Data arc : 52 hours (i.e. 4.5 hrs past P1)
* Assume periapsis thrusting (TH) is known accurately from telemetry data.

- PHASE/PURPOSE: Aerobraking; P= 40 hrs / Tp, Rp accuracy
  EPOCH (ET): 10/10/97, 23:05:00

	TRACKING DATA			ESTIMATION (3)	
	Doppler (mm/s)	Range (m)	Dif-D (mm/s)	Estimate	Consider
N :	807	--	--	State, AC,	Grav (25x25),
σ :	0.2	--	--	ρ_o(P1)	Density (P2), AC(P2), NG, GM4

Data arc : 44 hours (1 orbit plus 4.5 hours past periapsis)
Note the usage of two density models: a) a solve-for model during P1 and b) a density uncertainty of 30%, 60% and 90% during P2.

APPENDIX 9.10 INITIAL CONDITIONS FOR COVARIANCE ANALYSIS

- PHASE/PURPOSE — Aerobraking; P= 3.0 hrs / Tp, Rp accuracy
- EPOCH (ET) — 12/29/97, 00:59:45

	TRACKING DATA: Doppler (mm/s)	Range (m)	Dif-D (mm/s)	ESTIMATION (3,5): Estimate	Consider
N :	100	--	--	State, TH,	Grav (25x25),
σ :	0.2	--	--	ρ_o(P1, P2)	Density (P3, ...), TH(P3, ...), GM4 NG

Data arc : 7 hours (2 orbits and 1.5 hours past periapsis, P2)

- PHASE/PURPOSE — Walkout; P= 2.0 hrs / Tp prediction
- EPOCH (ET) — 1/10/98, 12:40:05

	TRACKING DATA: Doppler (mm/s)	Range (m)	Dif-D (mm/s)	ESTIMATION (7, 7A, 7B): Estimate	Consider
N :	60	--	--	State, TH(P1,P2),	Grav (25x25),
σ :	0.2	--	--	ρ_o (P1,P2), Grav (4x4)	NG Accel, GM4, ρ_o (P3, ...), TH (P3, ...)

Data arc : 5 hours (i.e. 1.5 hrs past P2- approx 2.5 orbits)
TH: thrusting around periapsis

- PHASE/PURPOSE — Mapping, Ipos=90 deg/ Position accuracy
- EPOCH (ET) — 10/28/98, 10:30:00

	TRACKING DATA: Doppler (mm/s)	Range (m)	Dif-D (mm/s)	ESTIMATION (6/B4): Estimate	Consider
N :	257	--	117	State,	Grav(25x25),
σ :	0.2	--	0.06	Grav(4x4)	Density, GM4

Data arc : 8-10 hours
The atmospheric density is nearly minimum (see Appendix 9.9)

APPENDIX 9.10 INITIAL CONDITIONS FOR COVARIANCE ANALYSIS

- PHASE/PURPOSE: Mapping, Initial/ Position accuracy
  EPOCH (ET): 03/11/98, 22:00:00

	TRACKING DATA			ESTIMATION (2,1)	
	Doppler (mm/s)	Range (m)	Dif-D (mm/s)	Estimate	Consider
N :	132	--	---	State,	Grav(25x25),
σ :	0.2	--	---	Grav(4x4)	Density, GM4, Stats, Pl Eph, NG

Data arc : 8-10 hours

Solution 2: Used expected improvement in gravity field due toGC

- PHASE/PURPOSE: Mapping, Perihelion/ Position accuracy
  EPOCH (ET): 11/24/99, 23:30:00

	TRACKING DATA			ESTIMATION (6/B4)	
	Doppler (mm/s)	Range (m)	Dif-D (mm/s)	Estimate	Consider
N :	132	--	---	State,	Grav(25x25),
σ :	0.2	--	---	Grav(4x4)	Density, GM4 Stats., Pl Eph NG

Data arc : 8-10 hours

APPENDIX 9.11 NAVIGATION FUNCTIONAL OVERVIEW

Navigation functions are centered on three main responsibilities: a) orbit determination to evaluate current and predicted orbital and trajectory parameters, b) orbit and trajectory and associated products generation and c) propulsion maneuver design for achieving changes in orbit and trajectory parameters. These functions are summarized in Fig. 9.11-1 with the related software, interfaces and input and output products.

Fig. 9.11-1 Overview of navigation software and interfaces.

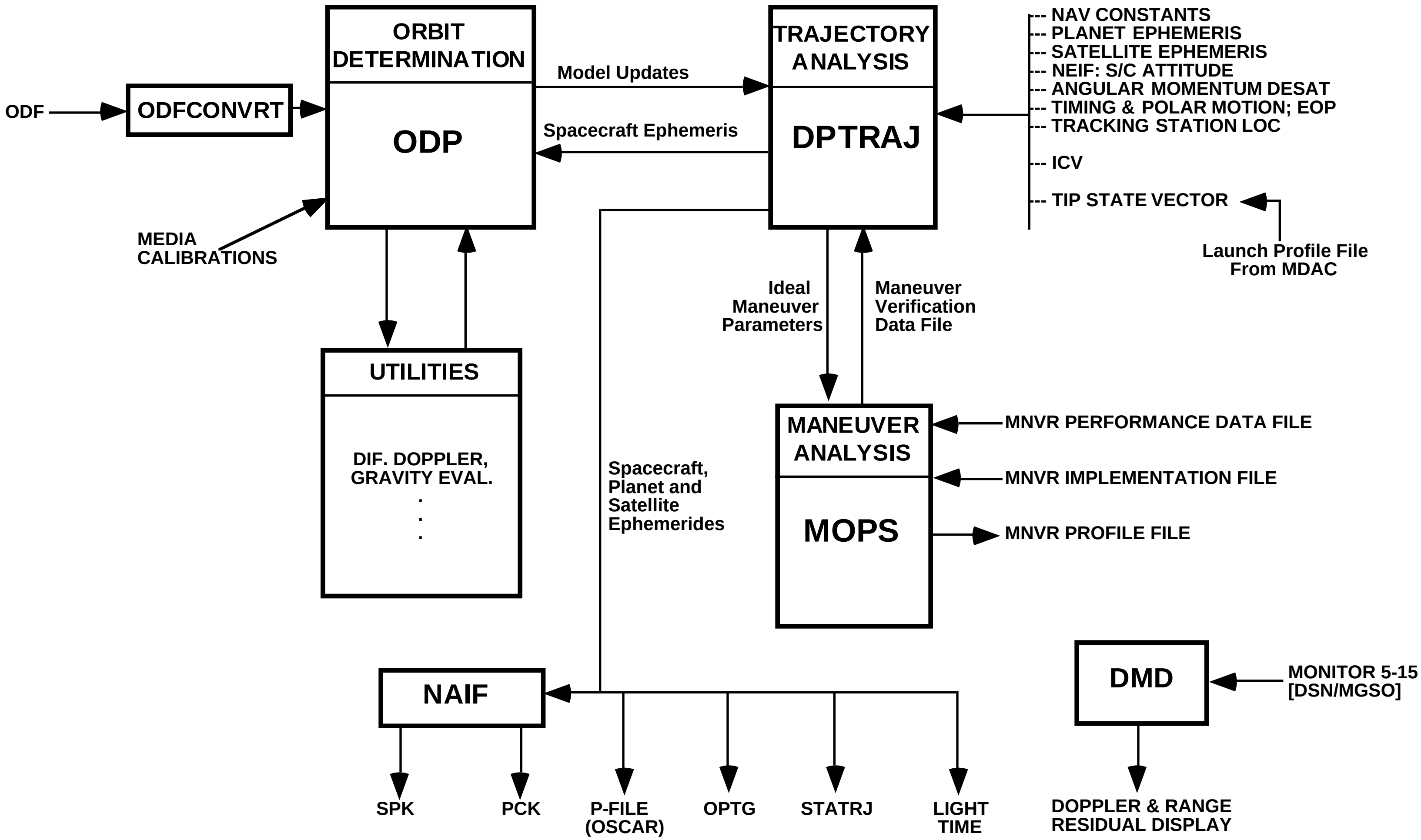

Fig 9.11-1 Overview of Navigation software and interfaces

APPENDIX 9.12 WORKSTATION AND LAN OVERVIEW

Fig. 9.12-1 Overview of Navigation Workstations and Network Connectivity.

Workstation	Model	RAM (MB)	Formatted Disk (GB)	LAN
ARES	HP 750	64	6.5	MM Nav
THARSIS	HP 750	64	3.5	MM Nav
mgnavhp1	HP 720	64	1.5	MGS
	SUN			
mgnav1	SPARC 2	48	3	MGS
mgnav2	SPARC 2	48	3	MGS
mgnav3	SPARC 2	48	2	MGS
mgnav4	SPARC 5	64	1.5	MGS
mgnav5	IPC	32	1.5	MGS
mgnav6	IPC	32	1	MGS

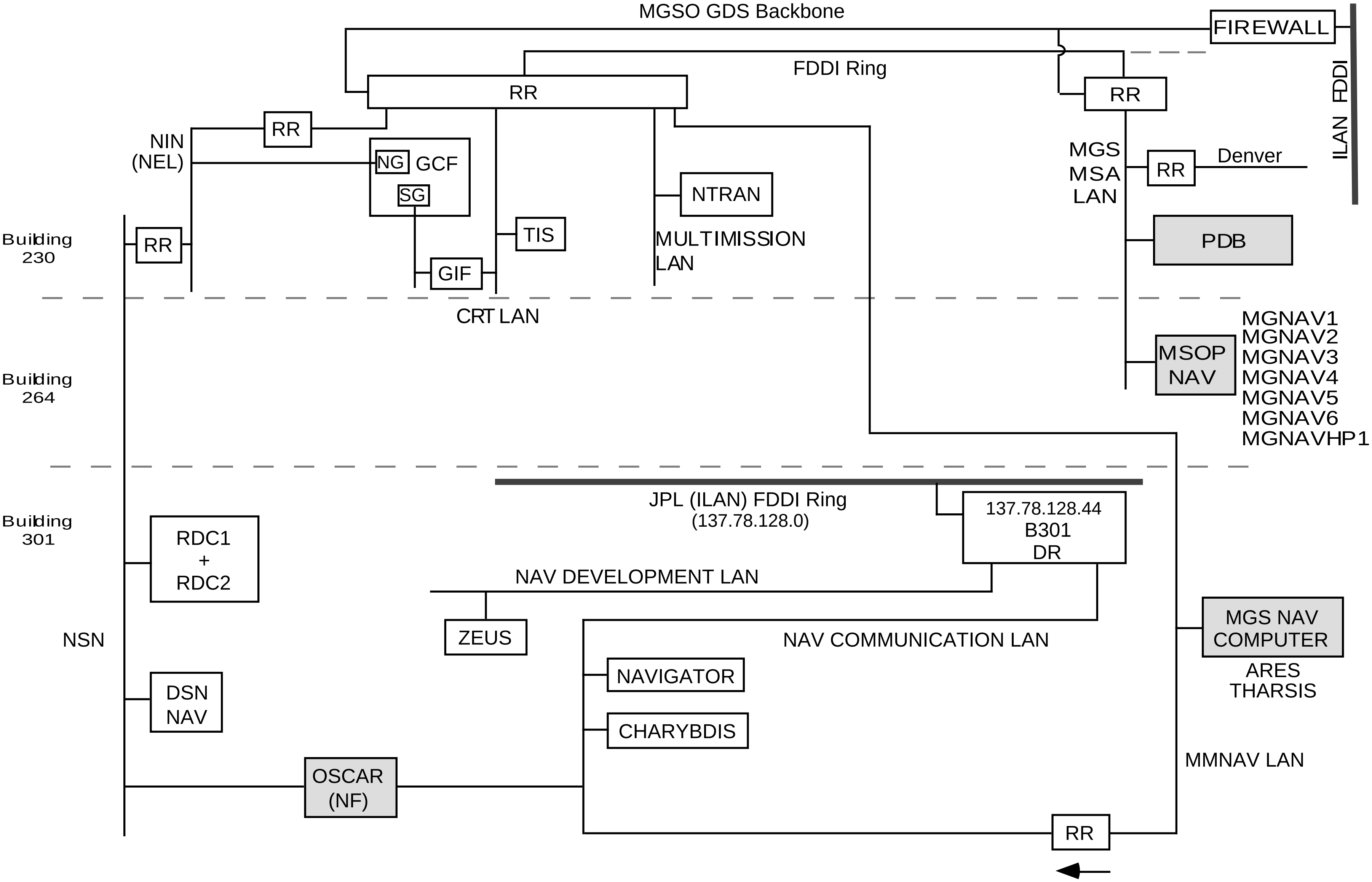

Fig 9.12-1 Overview of Navigation workstations and network connectivity

APPENDIX 9.13 PROCEDURES LIST

NAVIGATION OPERATIONAL PROCEDURES

NAV-0001 GVPSTATE / ICPREP EXECUTION - TARGET INTERFACE POINT (TIP) INITIAL CONDITIONS

NAV-0002 INTER-CENTER VECTOR (ICV) FILE TRANSFER FROM THE DSN INTERFACE (OSCAR) TO THE NAVIGATION TEAM

NAV-0003 ORBIT TRACKING DATA FILE (ODF) TRANSFER FROM THE DSN TO THE NAV TEAM

NAV-0004 TRANSFER OF MEDIA CALIBRATION, TIME AND POLAR MOTION, AND EARTH ORIENTATION PARAMETERS FILES FROM THE DSN INTERFACE (OSCAR) TO THE NAV COMPUTER

NAV-0005 ANGULAR MOMENTUM DESATURATION (AMD) FILE TRANSFER AND INPUT TO DPTRAJ

NAV-0006 NAVIGATION PROCESS: ORBIT DETERMINATION AND PROPULSIVE MANEUVER ASSESSMENT
- UPDATE STATE (GIN FILE)
- ANALYZE RADIOMETRIC DATA
- UPDATE MODEL PARAMETERS
- PROPAGATE STATE AND UNCERTAINTIES

NAV-0007 NAVIGATION PROCESS: DESIGN AND VERIFICATION OF PROPULSIVE MANEUVERS
- MANEUVER PERFORMANCE DATA FILE TRANSFER
- MANEUVER PROFILE FILE GENERATION
- MANEUVER IMPLEMENTATION FILE ASSESSMENT

NAV-0008 SPACECRAFT EPHEMERIS (P-FILE) GENERATION AND TRANSFER TO THE DSN/NAV INTERFACE (OSCAR)

NAV-0009 SPK FILE GENERATION AND TRANSFER TO THE PDB

NAV-0010 LIGHT TIME FILE GENERATION AND TRANSFER TO THE PDB

NAV-0011 STATION POLYNOMIAL (STATRJ) FILE GENERATION AND TRANSFER TO THE PDB

NAV-0012 ORBIT PROPAGATION, TIMING AND GEOMETRY FILE (OPTG) GENERATION AND TRANSFER TO THE PDB

NAVIGATION OPERATIONAL PROCEDURES (CONT)

NAV-0013 REAL TIME RADIOMETRIC DATA DISPLAY

NAV-0014 GENERATE AND ANALYZE DIFFERENCED DOPPLER DATA

NAV-0015 DETERMINE ATMOSPHERIC DENSITY MODEL PARAMETERS
ESTABLISH DATABASE FOR PREDICTION AND SHORT-TERM VARIATION

NAV-0016 DETERMINE MARS GRAVITY FIELD MODEL COEFFICIENTS

NAV-0017 GUIDELINES FOR PROPULSIVE MANEUVER MODEL / FILE SELECTION (OFF-THE-SHELF) THROUGHOUT AEROBRAKING

NAV-0018 MAINTAIN AND UPDATE NAVIGATION AEROBRAKING DATABASE
MONITOR AND PREDICT AEROBRAKING PROGRESS

NAV-0019 SFDU WRAP / UNWRAP AND PDB ACCESS FOR FILE TRANSFER

APPENDIX 9.14 OPERATIONAL INTERFACE AGREEMENTS (OIA)

NAVIGATION GENERATED OIAs

NAV-001	LIGHT TIME FILE
NAV-002	STATION POLYNOMIAL FILE (STATRJ)
NAV-003	SPACECRAFT EPHEMERIS FILE (P-FILE)
NAV-004	NAVIGATION TRIGGER FILE
NAV-005	ORBIT PROPAGATION AND TIMING GEOMETRY FILE
NAV-006	SP KERNEL (SPK) FILE
NAV-007	PLANETARY CONSTANTS KERNEL (PCK) FILE
NAV-008	MANEUVER PROFILE FILE
NAV-009	ORBIT NUMBER FILE

APPENDIX 9.15 ACRONYMS

AB	Aerobraking
ABM	Aerobraking Maneuver
AMD	Angular Momentum Desaturation
ANS	Array Normal Spin
AU	Astronomical Unit
B-plane	Interplanetary phase Mars centered, target coordinate system
BWG	Beam Wave Guide (DSN station)
C3	Measure of Injection Energy
DE	Development Ephemeris
Delta-V	Change in Velocity (ΔV)
Dif-D	Differenced Doppler data
DT, CT, R	Down-Track, Cross-Track, and Radial Components of Position
DSN	Deep Space Network
DSS	Deep Space Station
EME50	Earth Mean Equator and Equinox of 1950.0
ERT	Earth Receive Time
FOM	Figure of Merit
GC	Gravity Calibration
HEF	High Efficienty Stations (DSS 15, DSS 45 and DSS 65)
HGA	High Gain Antenna
IAU	International Astronomical Union
I	Injection
Ipos	Inclination of spacecraft's orbital plane with respect to the plane-of-the-sky (pos)
Isp	Specific impulse
J2000 ARS	J2000 Astronomical Reference System
L	Launch
LAMBIC	Linear Analysis of Maneuvers with Bound and Inequality Constraints
LGA	Low Gain Antenna
LGC	Longitude Grid Control
LMA	Lockheed Martin Aerospace
LTOF	Linearized Time Of Flight
MARS GRAM	Mars Global Reference Atmospheric Model
MGS	Mars Global Surveyor
MO	Mars Observer
MOI	Mars Orbit Insertion
MOPS	Maneuver Operations Program Set
MOS	Mission Operations System
MP	Mission Plan
MR	Mission Requirements
MRD	Mission Requirements Document

ACRONYMS

MRR	Mission Requirements Request
NAV	Navigation
NG	Non-gravitational
NTO	Nitrogen Tetroxide
OCM	Orbit Change Maneuver
OD	Orbit Determination
OPTG	Orbit Propagation, Timing and Geometry
OTM	Orbit Trim Maneuver
OWLT	One Way Light Time
REM	Rocket Engine Module
Rp	Radial distance at periapsis
RU	Range Unit
RWA	Reaction Wheel Assembly
SCET	Spacecraft Event Time
SEM	Sun-Earth-Mars
SMAA	Semi-Major Axis
SMIA	Semi-Minor Axis
SOL	One Mars day
Solar Beta Angle	Angle between the spacecraft's orbital plane and the vector to the sun
SPK	Spacecraft Planet Kernel
SRA	Sequential Ranging Assembly
SRM	Solid Rocket Motor
SRP	Solar Radiation Pressure
STOIC	Standby Timing Operations in Contingencies
TCD	Trajectory Characeristic Document
TCM	Trajectory Correction Maneuver
TDS	Tracking Data System
TECO	Third Stage Engine Cut Off
TIP	Target Interface Point
TMO	Transfer to Mapping Orbit
To	Initial Epoch or Time
Tp , Ta	Time of Periapsis Passage, Time of Apoapsis Passage
TSAC	Tracking System Analytical Calibration
TVC	Thrust Vector Control
USO	Ultra Stable Oscillator

APPENDIX 9.16 NOMINAL DELTA-V ALLOCATION FOR PROPULSIVE MANEUVERS

The following two tables, having been updated, provide the nominal allocation of Delta-V (m/s) for propulsive maneuvers (also for the spacecraft's attitude control fuel consumption) throughout the mission. During flight operations, the Project (SCT) shall monitor the Delta-V expended.

MARS GLOBAL SURVEYOR SPACECRAFT ΔV/PROPULSIVE PERFORMANCE

Launch Date - 11/6/96

Launch Period Open - Propellant Loading

MODIFIED MISSION SYSTEM CDR ΔV BUDGET

SPACECRAFT INJECTED MASS (kg) 1060.0

		MONOPROP TRANSLATIONAL		BIPROP TRANSLATIONAL		MONOPROP ROTATIONAL		PROPELLANT BREAKDOWN			POSTBURN	EST. BURN DURATION		
MISSION PHASE	MANEUVER	Isp (s)	ΔV Reqd (m/s)	Isp (s)	ΔV Reqd (m/s)	Isp (s)	ΔV Reqd (m/s)	M-HYDRZ (kg)	B-HYDRZ (kg)	NTO (kg)	S/C MASS (kg)	MONOPROP #T	MONOPROP (s)	BIPROP (s)
CRUISE ΔV95	TCM-1/2	220.0	0.0	317.0	49.9	220.0	0.3	0.15	9.12	7.76	1042.97	-	-	79.7
	TCM-3/4	220.0	3.0	255.0	0.0	220.0	0.0	1.45	0.00	0.00	1041.52	4	175.7	-
CAPTURE	MOI Rp = 3700 km Per = 48 Hr	220.0	0.0	317.0	975.6	220.0	5.9	2.84	151.64	128.90	758.14	-	-	1332.7
Aerobraking Walk-in	AB-1	220.0	0.0	315.0	8.0	220.0	0.1	0.04	1.06	0.90	756.14	-	-	9.2
	AB-2	220.0	1.5	255.0	0.0	190.0	0.0	0.53	0.00	0.00	755.62	4	63.7	-
	AB-3	220.0	0.5	255.0	0.0	190.0	0.0	0.18	0.00	0.00	755.44	4	21.2	-
	AB-4	220.0	0.5	255.0	0.0	190.0	0.0	0.18	0.00	0.00	755.27	4	21.2	-
Aerobraking Main Phase	ABM Translation	220.0	5.0	255.0	0.0	190.0	0.0	1.75	0.00	0.00	753.52	-	-	-
	ABM Rotation	220.0	0.0	255.0	0.0	190.0	5.0	2.02	0.00	0.00	751.50	-	-	-
Aerobraking Walk-out	ABM Translation	220.0	20.0	255.0	0.0	190.0	0.0	6.93	0.00	0.00	744.57	-	-	-
	ABM Rotation	220.0	0.0	255.0	0.0	190.0	30.0	11.89	0.00	0.00	732.67	-	-	-
	ABX	220.0	0.0	317.0	60.2	220.0	0.4	0.14	7.60	6.46	718.49	-	-	66.3
TransMap	TMO	220.0	0.0	317.0	16.1	220.0	0.1	0.03	2.01	1.71	714.74	-	-	17.5
Mission Contingency	Aerobraking Pop-Up	220.0	2.5	315.0	14.5	190.0	0.0	0.83	1.81	1.54	710.57	-	-	15.7
	ΔV Reserves	220.0	2.0	315.0	13.5	190.0	0.0	0.66	1.67	1.42	706.82	-	-	14.5
	OTM-1 (Frzn)	220.0	0.0	315.0	7.5	190.0	0.0	0.00	0.93	0.79	705.11	-	-	8.0
MAPPING Drag Dens 95%	OTM (Drag/GTE)	220.0	3.9	255.0	0.0	190.0	0.0	1.27	0.00	0.00	703.83	-	-	0.0
	ACS Rotation	220.0	0.0	255.0	0.0	190.0	40.0	14.95	0.00	0.00	688.89	-	-	-
ADDITIONAL ΔV REQUIRED	QUARANTINE ORBIT (PQ)	220.0	17.0	255.0	0.0	190.0	0.0	5.41	0.00	0.00	683.48	4	655.3	-
RELAY Drag Dens 95%	OTM (Drag)	220.0	1.0	255.0	0.0	190.0	0.0	0.32	0.00	0.00	683.16	-	-	-
	ACS Rotation	220.0	0.0	255.0	0.0	190.0	2.0	0.73	0.00	0.00	682.43	-	-	-
	SUB-TOTALS		56.90		1145.25		83.80	52.28	175.83	149.46				
	MISSION TOTAL ΔV		1285.95			S/C Dry Mass (kg)	673.89	S/C Dry Mass Capability (kg)			673.89			

Injected Mass Breakdown (kg)		Mission Total ΔV Breakdown	
Spacecraft Dry	673.9	Translational ΔV	1202.2
Hard Ballast	0.00	Rotational ΔV	83.8
Total Propellant	386.1	Bipropellant ΔV	1145.3
Total Inj Mass	1060.0	Monopropellant ΔV	140.7
		Total Mission ΔV	1286.0

Prop Tanks	Load Error	Max Usable[1]	Desired Usable	Total Load Plus Error[2]	Full Tanks (100% Fill)[3]	Fill Level (Percent)	PROPELLANT (kg)	
							Usable	377.57
N204	0.37	164.90	149.46	152.82	177.32	86.18%	Unusable 2%	7.55
(2x) N2H4	0.62	230.20	228.11	233.30	246.94	94.47%	Load Error	0.99
Ge (m/s^2)		9.80665	Engine Thrust (N)	BIPROP	658.7		Oxidizer Ballast	0.00
BIPROP MIX RATIO		0.85		MPROP	4.45		Total Prop	386.11

[1]5% Ullage [2]85% N2O4 Fill = 150.7 kg [3]Per Dominick Oxidizer Ballast (1=Y/2=N) 1

MSN DV - FNP 96/08

MARS GLOBAL SURVEYOR SPACECRAFT MANEUVER EXECUTION

Modified Mission System CDR ΔV Budget (5/96)

Launch Date - 11/25/96

(Minimum Spacecraft Mass at Aerobraking Start)

SPACECRAFT INJECTED MASS (kg)	1060.00
Spacecraft Dry Mass (kg)	673.89
Ballast (kg)	0.00
Total Propellant (kg)	386.11

Engine Thrust (N)		Propellant Tanks	Load Error	Usable Load	Usable Plus Error	Max Usable*	Unusable 2%	Oxidizer Ballast	Tank Totals	Tank Redlines	Ge (m/s^2) 9.80665
BIPROP	658.7	NTO (kg)	0.37	149.46	149.83	164.9	2.99	0	152.82	3.36	BIPROP MIX RATIO
MPROP	4.45	(2x) N2H4 (kg)	0.62	228.11	228.73	230.2	4.56	-	233.29	5.18	0.85

*5% Ullage

MISSION PHASE	MANEUVER	MONOPROP TRANSLATIONAL Isp (s)	MONOPROP TRANSLATIONAL ΔV Reqd (m/s)	BIPROP TRANSLATIONAL Isp (s)	BIPROP TRANSLATIONAL ΔV Reqd (m/s)	MONOPROP ROTATIONAL Isp (s)	MONOPROP ROTATIONAL ΔV Reqd (m/s)	PROPELLANT USAGE M-HYDRZ (kg)	PROPELLANT USAGE B-HYDRZ (kg)	PROPELLANT USAGE NTO (kg)	PROPELLANT REMAINING HYDRZ (kg)	PROPELLANT REMAINING NTO (kg)	POSTBURN S/C MASS (kg)	BURN DURATION #T	BURN DURATION (s)
CRUISE *ΔV95*	TCM-1/2	220.0	0.0	317.0	49.9	220.0	0.3	0.15	9.12	7.76	224.02	145.06	1042.98	n/a	79.7
	TCM-3/4	220.0	3.0	255.0	0.0	220.0	0.0	1.45	0.00	0.00	222.57	145.06	1041.53	4	175.7
CAPTURE	MOI Rp = 3700 km Per = 48 Hr	220.0	0.0	317.0	981.3	220.0	5.9	2.84	152.40	129.54	67.33	15.53	756.75	n/a	1339.5
Aerobraking Walk-in	AB-1	220.0	0.0	315.0	8.0	220.0	0.1	0.04	1.06	0.90	66.24	14.63	754.75	n/a	9.2
	AB-2	220.0	1.5	255.0	0.0	190.0	0.0	0.52	0.00	0.00	65.71	14.63	754.23	4	63.6
	AB-3	220.0	0.5	255.0	0.0	190.0	0.0	0.17	0.00	0.00	65.54	14.63	754.06	4	21.2
	AB-4	220.0	0.5	255.0	0.0	190.0	0.0	0.17	0.00	0.00	65.36	14.63	753.88	4	21.2
Aerobraking Main Phase	ABM Translation	220.0	5.0	255.0	0.0	190.0	0.0	1.75	0.00	0.00	63.62	14.63	752.14	-	-
	ABM Rotation	220.0	0.0	255.0	0.0	190.0	5.0	2.02	0.00	0.00	61.60	14.63	750.12	-	-
Aerobraking Walk-out	ABM Translation	220.0	11.0	255.0	0.0	190.0	0.0	3.81	0.00	0.00	57.79	14.63	746.30	-	-
	ABM Rotation	220.0	0.0	255.0	0.0	190.0	26.5	10.54	0.00	0.00	47.25	14.63	735.77	-	-
	ABX	220.0	0.0	317.0	65.8	220.0	0.4	0.14	8.33	7.08	38.78	7.55	720.22	n/a	72.7
TransMap	TMO	220.0	0.0	317.0	17.9	220.0	0.1	0.03	2.24	1.90	36.51	5.65	716.05	n/a	19.5
Mission Contingency	Aerobraking Pop-Up	220.0	2.5	315.0	14.1	190.0	0.0	0.83	1.76	1.50	33.92	4.15	711.96	n/a	15.3
	ΔV Reserves	220.0	11.6	315.0	0.0	190.0	3.5	5.14	0.00	0.00	28.78	4.15	706.82	n/a	0.0
	OTM-1 (Frzn)	220.0	0.0	315.0	7.5	190.0	0.0	0.00	0.93	0.79	27.86	3.36	705.11	n/a	8.0
MAPPING *Drag Dens 95%*	OTM (Drag/GTE)	220.0	3.9	255.0	0.0	190.0	0.0	1.27	0.00	0.00	26.58	3.36	703.84	-	-
	ACS Rotation	220.0	0.0	255.0	0.0	190.0	40.0	14.95	0.00	0.00	11.64	3.36	688.89	-	-
ADDITIONAL ΔV REQUIRED	QUARANTINE ORBIT (PQ)	220.0	17.0	255.0	0.0	190.0	0.0	5.41	0.00	0.00	6.23	3.36	683.48	4	655.3
RELAY *Drag Dens 95%*	OTM (Drag)	220.0	1.0	255.0	0.0	190.0	0.0	0.32	0.00	0.00	5.91	3.36	683.16	-	-
	ACS Rotation	220.0	0.0	255.0	0.0	190.0	2.0	0.73	0.00	0.00	5.18	3.36	682.43	-	-
	SUB-TOTALS		57.5		1144.5		83.8	52.28	175.83	149.46	S/C Dry Mass (kg)		673.89		
	MISSION TOTAL ΔV	1285.8													

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